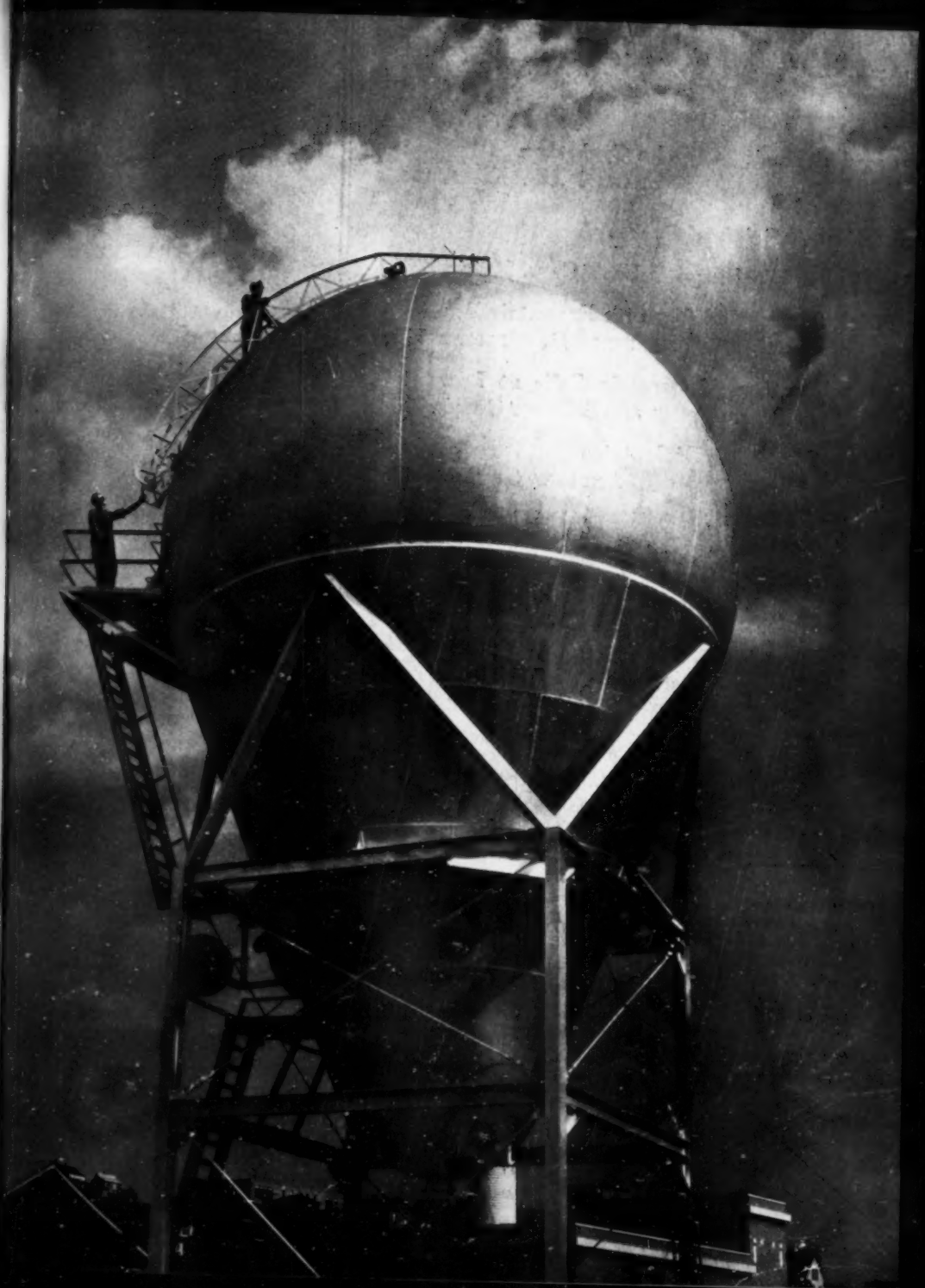
JOURNAL OF APPLIED PHYSICS



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Journal of Applied Physics

Volume 9 November, 1938 Number 11

Nuclear Physics and Scientific Journalism

ONE of the most recent paradoxes of modern physics is the use of equipment rising fifty to sixty feet in the air to investigate properties of atomic nuclei which are no larger than one million-millionth part of a centimeter in diameter. Our astonishment at this paradox increases when we realize that the nuclear physicist must not only be able to manipulate the most delicate instruments but also he must design towering engineering structures; he must calculate effects of 100 lb./in.^{2} pressures on huge boiler-like tanks and he must provide insulation for voltage far higher than those used for even the largest transmission lines. He must become something of a superplumber to build vacuum systems of large iron pipe fittings with ion tubes fifty feet long. These abilities are just a few of the requirements if he works with high pressure electrostatic generators. If on the other hand he constructs cyclotrons to investigate the atomic nucleus, we find him placing orders for hundreds of tons of iron, for enormous quantities of copper conductors, and we find him designing electromagnetic oscillators that rival those of a large radio station. All these things go to make up the equipment needed to learn more about what is believed to be the tiniest particle in existence.

It is the purpose of this issue of the *Journal of Applied Physics* to bring readers into close touch with the design, construction and beauty of these new physical tools. The subject matter is spectacular and according to many people demands a spectacular treatment. In some respects this issue is an experiment in an attempt to meet this demand. We are presenting the story of the development of these nuclear tools in pictures as well as in text. We believe that in recording details and showing designs there is no medium of expression which is more suitable than that of photography. The reproduction of these photographs is expensive and the decision as to whether or not similar articles should be published in other branches of physics must be left to the readers. If a sufficient number of readers are interested, this type of scientific paper can be continued. The *Journal of Applied Physics* is your journal and your comments will be of great help in guiding the editorial policy.—

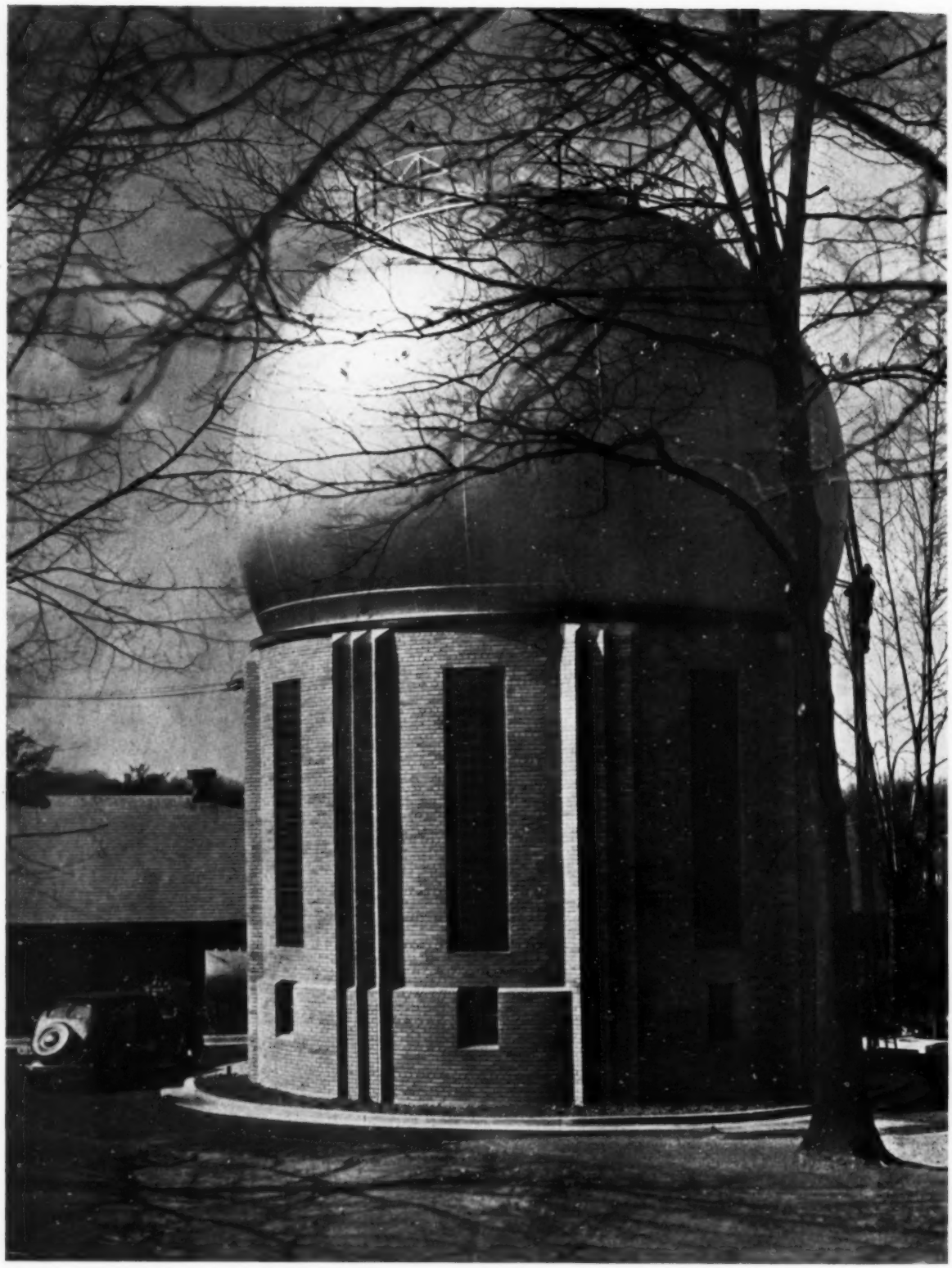
THE EDITOR.

For December

Penetration of Oil Sprays, by P. SCHWEITZER

Evidence for the Existence of a New Elementary Particle, by E. E. WITMER AND M. A. POMERANTZ

Original research papers on Clean-Up Pressure Effects in Low Pressure Mercury Vapor Discharges: A Reversible Electrical Clean-Up of Mercury, Evaluation of Yield Values with the Sphere Viscometer, and On the Symmetry of the Benzene Ring.



The beautiful housing of the Van de Graaff generator now under construction at the Carnegie Institution of Washington.

Production of High Energy Particles

A Review of the Recent Progress in the Development of Extremely High Voltages

BY W. H. WELLS

Westinghouse Research Laboratories
East Pittsburgh, Pennsylvania

AFTER the discovery by Rutherford in 1919 of the disintegration of nitrogen under bombardment by natural radioactive alpha-particles, it was realized that, to carry such work forward, attempts would have to be made to produce high speed nuclear particles by means of electric sources. A number of possibilities were apparent at that time and many of them have been developed considerably since that time. It is the purpose of this paper to review the progress which has been made during the past decade.

One of the earliest attempts to gain information about the interactions of high energy nuclear particles at close distances by means of artificially accelerated particles was undertaken in 1926 by the Department of Terrestrial Magnetism, Carnegie Institution of Washington, under the supervision of Gregory Breit, ably aided somewhat later by his colleagues, M. A. Tuve, L. R. Hafstad, and O. Dahl. By using a Tesla coil and oil under pressure of 500 pounds per sq. in. to increase its breakdown strength, voltages in excess of 5 million volts were attained.[1] To accelerate the ions a vacuum tube was necessary which would withstand very high voltages. Considerable research finally lead to the successful adaptation of the cascade electrode tube principle of Coolidge to an accelerating tube which withstood voltages as high as 1900 kilovolts. The design is shown in Fig. 2a. It was found that voltages of over 400 to 500 kilovolts per gap could not be applied to a vacuum tube; in fact, about 400 kilovolts is the maximum so far used successfully on any vacuum tube. The principle of operation of the tube lies in the fact that voltages applied over the gap between two concentric cylinders give electric lines of force which tend to focus charged particles in an entirely analogous way to the focusing of light by simple lenses.[2] This principle of the use of gaps as electron lenses in one form or another enters into practically every method of accelerating particles to high energies. The focal length of a given electrode combination depends only on the ratio of the kinetic energy of the particle incident on the lens to the energy gained by the particle in the lens for a determined geometric shape of electrode surfaces. This means that once an accelerating tube has been adjusted with correct voltages over the gaps so as to focus one type of particle, for example, electrons, the same setting

FIG. 1. One of the most useful tools for the study of the nucleus of the atom, the Van de Graaff generator now nearing completion at the Westinghouse Research Laboratories.

is sufficient to cause protons, deuterons, alpha-particles, or other ions to focus at the target end of the tube in the same geometric paths. The tube shown in the photograph was used to accelerate both electrons and ions through 1100 kilovolts and to check the range-energy relation for protons by their range in a Wilson cloud chamber.[3]

With the successful development of an accelerating tube, capable of withstanding high voltages,

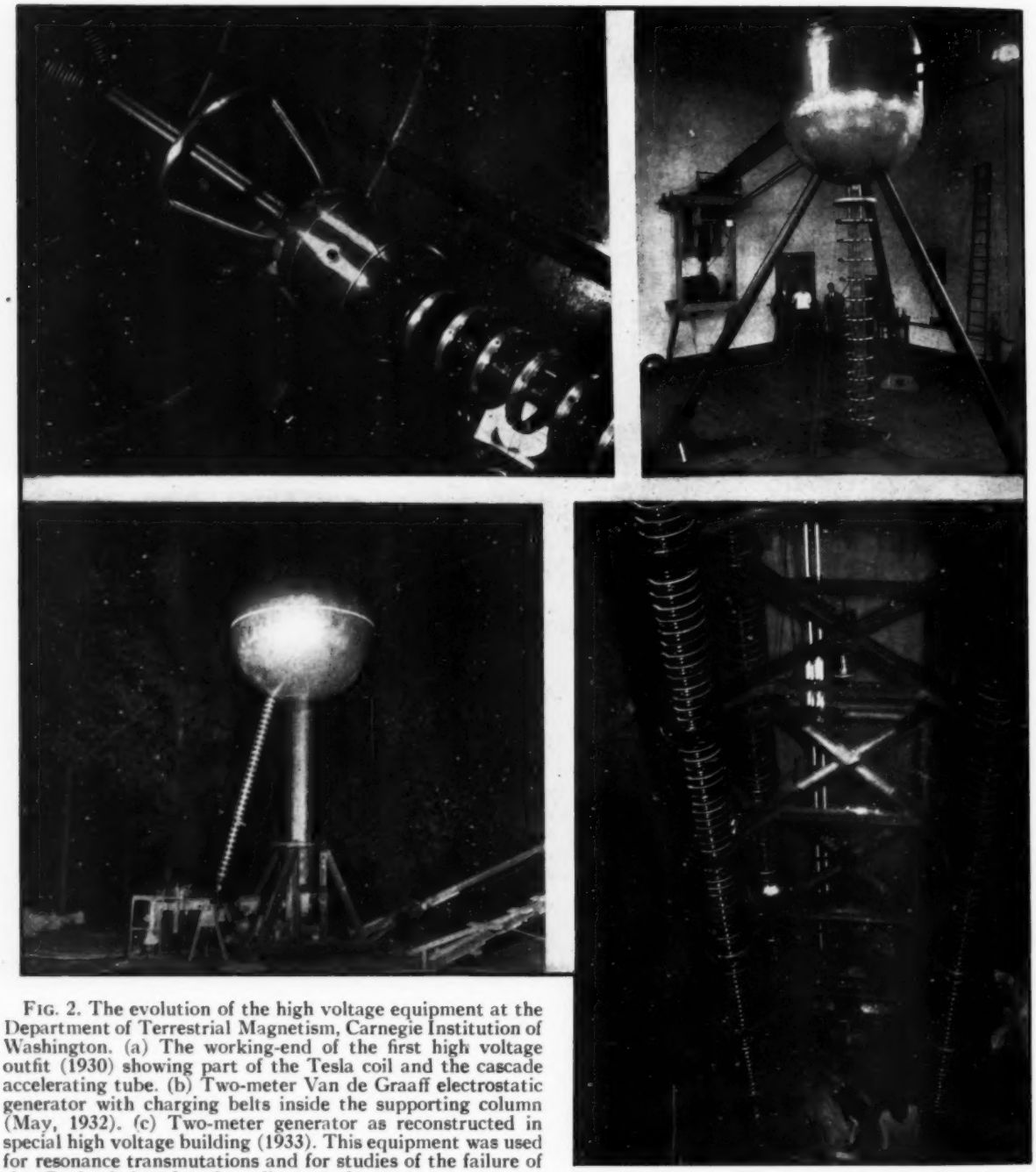


FIG. 2. The evolution of the high voltage equipment at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. (a) The working-end of the first high voltage outfit (1930) showing part of the Tesla coil and the cascade accelerating tube. (b) Two-meter Van de Graaff electrostatic generator with charging belts inside the supporting column (May, 1932). (c) Two-meter generator as reconstructed in special high voltage building (1933). This equipment was used for resonance transmutations and for studies of the failure of the Coulomb law for close distances between two protons. (d) Porcelain columns and steel platforms forming support of the 19-foot sphere of the new Carnegie Institution high voltage generator now under construction. The housing for this equipment is shown on p. 676.

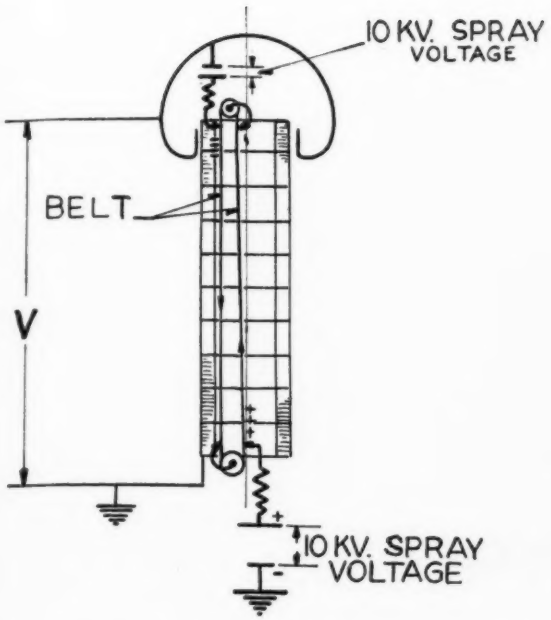


FIG. 3. Schematic diagram of a belt machine in which an electric charge of one sign is sprayed on belts from a series of points and is carried up on belt to the electrode where it is replaced by corona with an opposite charge which is carried down to grounded end.

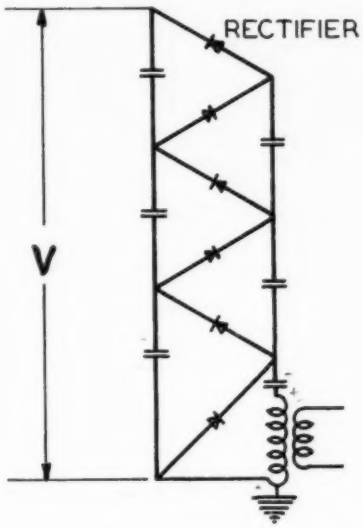


FIG. 4. Greinacher voltage multiplying circuit (used by Cockcroft and Walton) in which rectifiers pass current on the positive half-cycle only. Thus after a number of cycles the condensers are each charged to voltage which is determined by the input voltage, provided only a small power is drawn.

the Carnegie workers turned their attention to more useful means of producing high voltage. The Tesla coil arrangement suffered from the defect of a wide spread of energies of the particles as well as from the very short on-time of the high voltage which made it unsuitable for many types of experiments.

About this same time (1931), R. J. Van de Graaff at Princeton University had successfully modernized the type of endless belt electrostatic generator now usually designated by his name.[4] The method of operation of such a belt machine

FIG. 5. Cockcroft and Walton's first installation using voltage multiplier circuit.

is illustrated in Fig. 3. Tuve and his co-workers at the Carnegie Institution, in cooperation with Van de Graaff, tried two of his first units using two-foot spheres. With the aid of one of the cascade type accelerating tubes, it was shown that steady d.c. voltages could be successfully used for acceleration of nuclear particles at voltages of around 500 kilovolts.

Because of the success of these tests it was decided to construct a two-meter sphere gener-

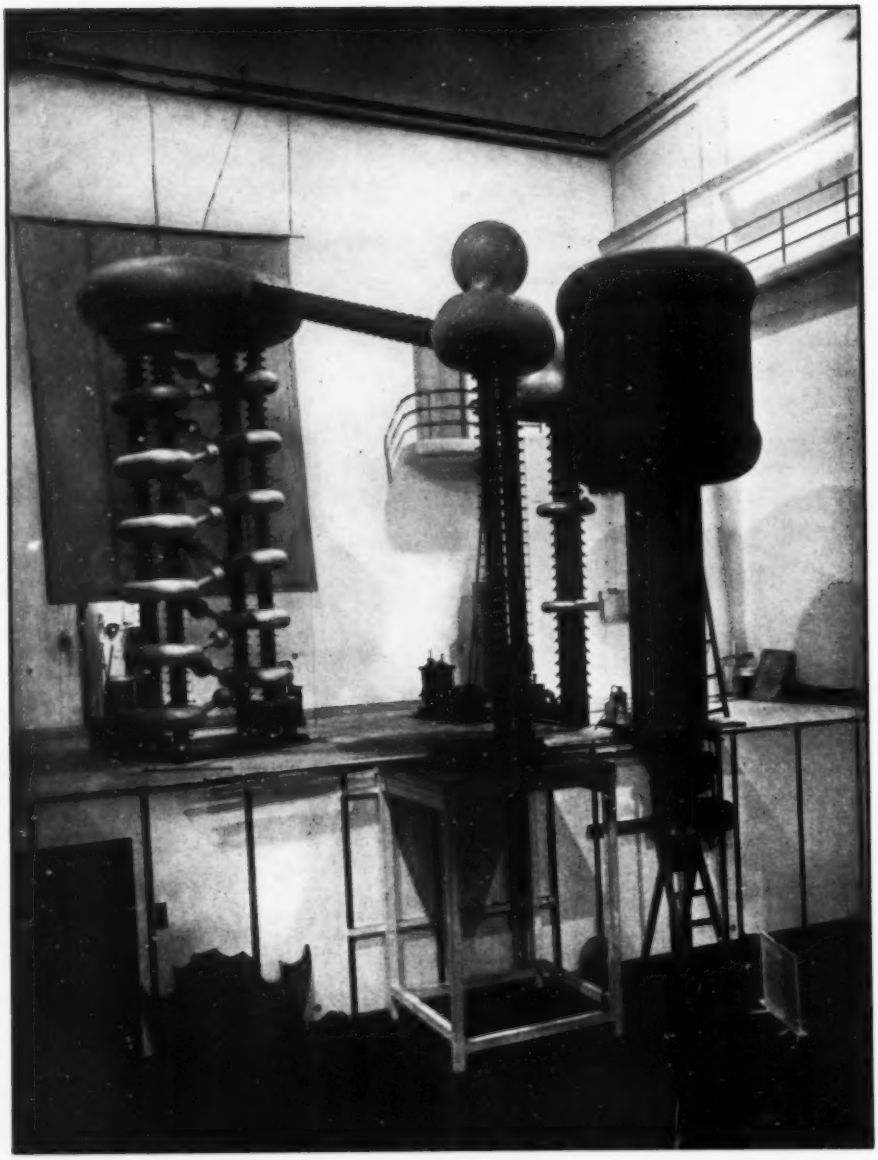


FIG. 6. Commercial 1200 kv voltage multiplier equipment recently installed at Cavendish Laboratory, Cambridge, England.

ator for voltages of over one million volts. In the summer of 1932 this voltage was successfully applied to an accelerating tube. The test was made out-of-doors (Fig. 2b) while awaiting the construction of a suitable building to house the generator at Carnegie Institution in Washington.

During the time of these outdoor tests, J. D. Cockcroft and E. T. S. Walton at the Cavendish Laboratory, Cambridge University, England, succeeded in causing the first disintegration using artificially accelerated particles. They used protons impinging on a lithium target and succeeded in demonstrating that two high energy alpha-particles were among the products of one mode of disintegration. To produce a high voltage, they employed a voltage multiplying circuit using rectifiers,[5] the operation of which can be seen from Fig. 4, where the arrows show the direction of current through the rectifiers. By the use of a two-section cascade tube they were able to accelerate particles up to 600 kilo-electron-volts energy. This important work showed that the wave-mechanical formulae for penetration of potential barriers was essentially correct in estimating that with a given voltage available for acceleration it would be easier to cause disintegrations using smaller mass particles than alpha-particles.

These results of Cockcroft and Walton were almost immediately verified by Lawrence, Livingston, and White, and by Lawrence and Henderson using the newly constructed cyclotron[6] at the University of California, and also by Tuve, Hafstad, and Dahl[7] with the one-meter electrode belt machine which they had just completed.

The cyclotron method of obtaining high voltage ions is the subject of another paper in this issue and the method will be merely outlined here. It consists in having repeated accelerations

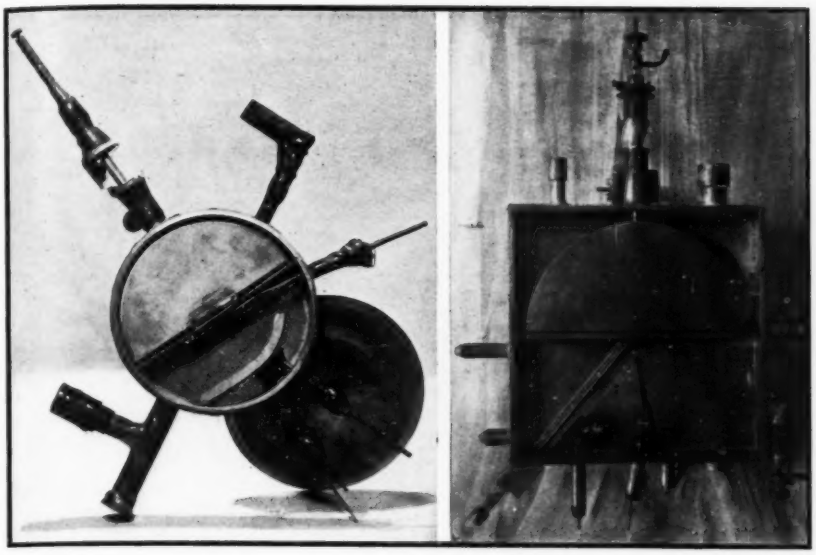


FIG. 7. Early form of the Lawrence cyclotron.

of the ions in the gaps between two hollow hemi-cylinders placed in a magnetic field. Ions introduced into these cylinders are caused to move in a spiral path with a time of transit around the path which is independent of the radius and hence of the energy. Thus, the ions continue to circulate in larger and larger circles as long as they stay in the central plane of the accelerating electrode. The number of complete paths per unit time depends upon the ratio of mass to charge of the particle, and it can be shown that for electrons the frequency would probably be higher than it is possible to attain with any of the present power oscillators. For both electrons and ions, there is a limitation to the maximum velocities since the relativistic increase of mass requires that the magnetic field be increased with increasing radius and that such a field would tend to defocus the ions from the central plane. This limitation[8] has not yet come into play for about 7 million electron-volt (Mev) deuterons, and when it does, it can probably be compensated by applied magnetic inhomogeneities of the field or by properly chosen electrostatic fields. For electrons, the difficulties seem at present to be much more severe so that some other methods probably will be used to attain very high energy electrons of 10 Mev or more.

FIG. 8. Magnet of University of California's new cyclotron now under construction.

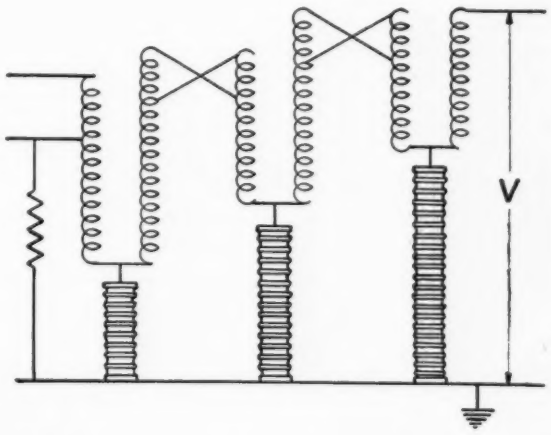


FIG. 9. Arrangement of cascade transformers in which the primary of each successive high voltage transformer is powered from a fraction of the secondary voltage of the previous one.

With the cyclotron, intensities of beam of up to 50 microamperes of deuterons have been obtained at the periphery of the hemi-cylinders and still higher currents have been measured circulating around nearer the center. It has been possible to bring a portion of the beam to a point several feet from the accelerating chamber so that it should always be possible to obtain a

uniform energy group of particles at the expense of intensity for experimentation when desired. By using deuterons for bombarding particles on targets of lithium, beryllium and boron, it has been possible to produce neutrons of an order of magnitude of 10^{10} per sec. as estimated by Lawrence. Because of the wandering of the central position of ion formation and perhaps because of inhomogeneities of the magnetic field, the beams from the cyclotron are not of as uniform energy as is desirable in many experiments, so that their use has been confined mainly to nuclear reactions which lead to the production of new artificially radioactive isotopes. Of great importance is the fact that it has also been possible to cause disintegrations in elements as heavy as bismuth with incident deuterons, definitely showing that very high voltages of 20 to 50 million volts will not be necessary for the disintegration of even the heaviest elements. About thirty cyclotrons have been projected and are either in development or completed at the present time, attesting to the widespread popularity of the method.

Other developments to accelerate nuclear particles were being carried out at different laboratories of which that due to Lauritsen, Crane, Soltan and their subsequent coworkers was one of the most productive in experimental material. In 1928, Lauritsen and Bennett[9] reported the successful focusing with a.c. of electrons up to 800 kilovolts for the production of x-rays for deep therapy at the Kellogg Radiation Laboratory of California Institute of Technology. They used a cascade transformer set for the high voltage. Subsequently, this available voltage was used to accelerate helium and deuterium ions, with intensities of production of neutrons from Be compara-

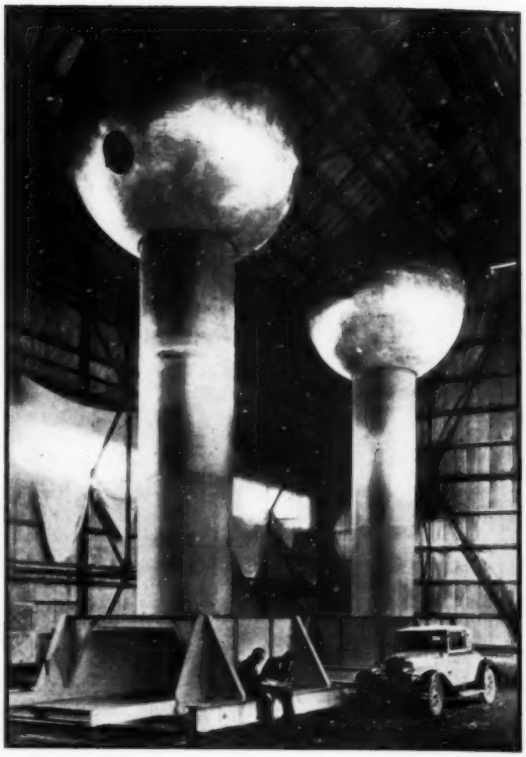


FIG. 11. Original Van de Graaff generator of the Massachusetts Institute of Technology erected at Round Hill.

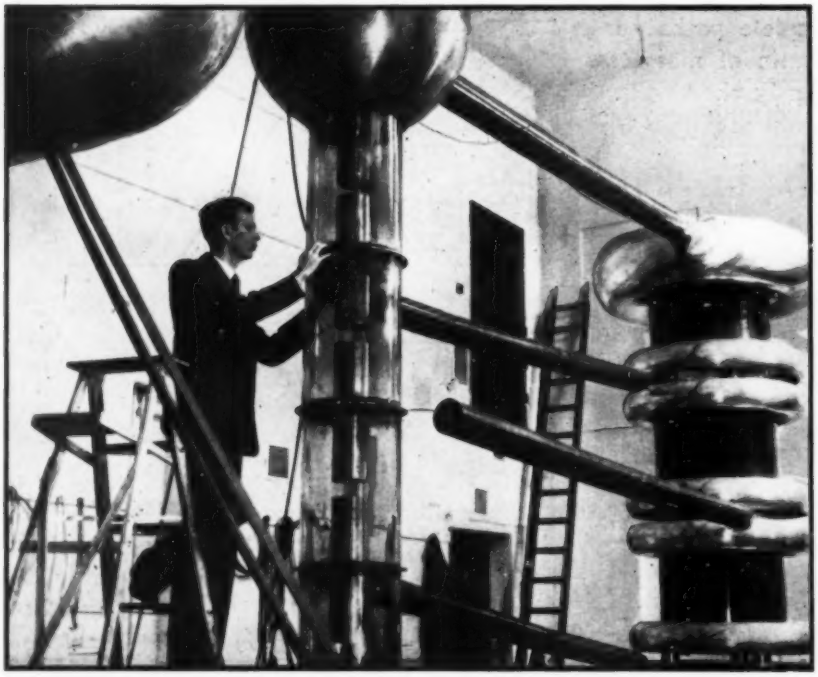


FIG. 10. Cascade transformer set used by Crane at University of Michigan.

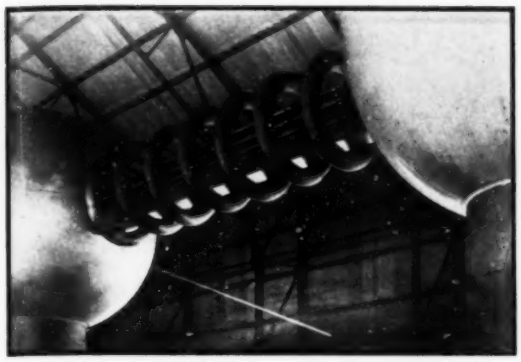


FIG. 12. Electron beam tube between the 15-foot spheres of Round Hill generator.

ble with those available from natural sources of alpha-particles. Since the ions are accelerated by a.c. voltage, it has not been possible to run accurate curves of efficiency of production of disintegration particles, so that much of their work has been confined to measurements of the energies of neutrons and gamma-rays produced with consequent determinations of the masses of the nuclei involved in the reactions. More recently, Crane (Fig. 10) installed a somewhat similar apparatus at the University of Michigan, in which taps from the high voltage transformer were used to distribute the voltage over the gaps of the accelerating tube.

About 1932–33, Van de Graaff projected the construction of an enormous belt machine at Round Hill, Massachusetts,[10] in association with Massachusetts Institute of Technology. Two electrodes, fifteen feet in diameter were used. The plan was to run one positive and one negative with a horizontal vacuum tube between them. This experimental arrangement, Fig. 11, showed that it was possible to get voltages of about 2.4 million volts positive and 2.7 million volts negative against adverse conditions of humidity[11] with belt currents of several milliamperes. With this installation an electron beam was focused down the tube at about 2 Mev. After the Round Hill installation had established the feasibility of the method, the equipment was moved to Cambridge to be re-erected in a large research center near commercial sources of supply. The terminals were set up in contact to obtain in effect a single-terminal generator with belts in one column and vacuum tube in the other, because of the resulting advantage in safety, precision, and speed of operation. The present installation is well suited for nuclear research on resonance disintegrations and with multiply-charged ions. In addition, yield calculations suggest its usefulness as a neutron generator in the production of artificial radioactivity. This latter possibility is now being investigated.

It has long been realized that an electrostatic machine of small dimensions might be made to

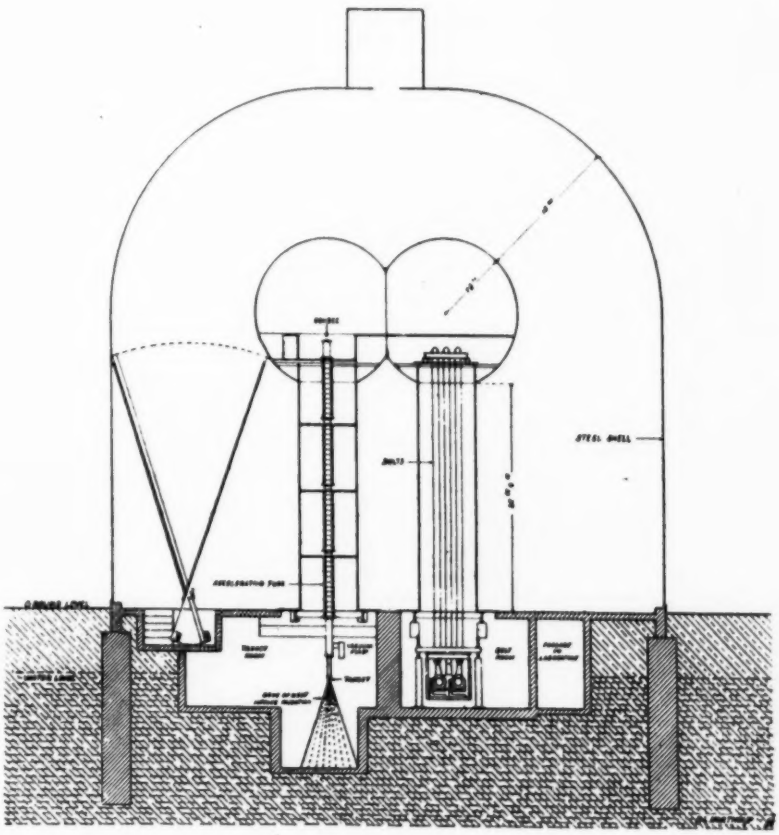


FIG. 13a. Diagram of Cambridge, Massachusetts, installation now being completed by Massachusetts Institute of Technology group.

operate in either vacuum or compressed gas.[12] At Princeton University[13] about 1 million volts were obtained with a cylindrical drum and 7 atmospheres pressure with about 100 microamperes charging current, but this voltage was not applied to an accelerating tube. Attempts were made to evacuate the cylinder for high breakdown strength both at Princeton and by Herb[14] at the University of Wisconsin, without success.

Herb continued with the use of air under pressure for insulating strength with marked success with the arrangement shown in Fig. 14, which attained 400 kilovolts at about 45 lbs. per sq. in. air pressure. This success led to the development of a larger unit, Figs. 15 and 16, which has attained 2.5 Mev protons with a steady voltage control of under 1 percent.

Shortly before this time, the 2-meter belt machine at Carnegie Institution of Washington was erected indoors (Fig. 2b) and it was found possible to control and measure by calibrated resistances, voltage of 1200 kilovolts maximum to about 1 percent.[15] This control culminated in the accurate measure of the scattering of protons at close distances of approach showing that there was an attractive force between two protons at distances comparable with the dimensions of nuclei.[16] It is now believed that this attractive force also holds between neutron and neutron and between neutron and proton.

FIG. 13b. External view of new Massachusetts Institute of Technology installation.

FIG. 13c. Internal arrangement of high voltage electrodes in new Massachusetts Institute of Technology installation.

Further measurements at higher voltages now in progress by Herb and his co-workers[17] at Wisconsin up to 2.5 million volts will do much to clarify the magnitude of these binding forces for elementary heavy particles.

The success of the experiments of the Wisconsin group indicated that it was worthwhile to

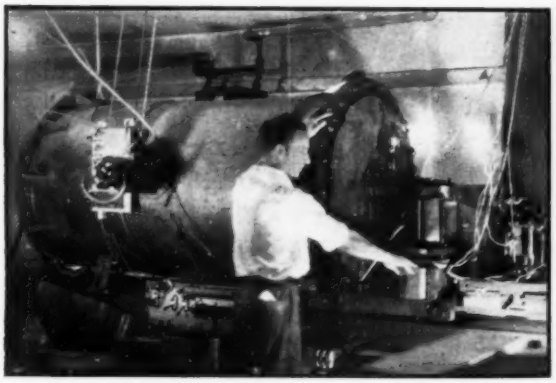


FIG. 14. First pressure belt machine used by Herb at University of Wisconsin to give 400 kilovolts. Scale $\frac{3}{4}$ in. = 1 ft.

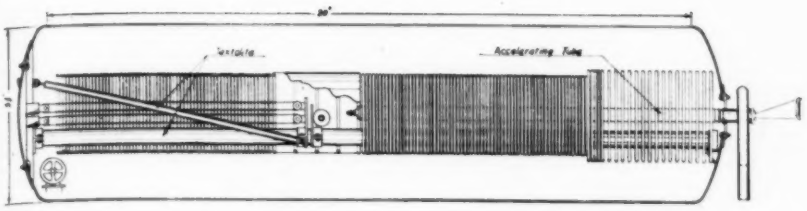


FIG. 15. Diagram of R. G. Herb's pressure generator now in use in the study of nuclear problems.

continue with the use of high pressure for insulation of the high voltage terminal, and large generators of this type are now nearing completion at the Westinghouse Research Laboratories at Pittsburgh, at Carnegie Institution of Washington, and at the University of Minnesota.

The Westinghouse generator is housed in a steel, pear-shaped container of diameter 30 ft. and 47 ft. in length designed for a working pressure of 120 lb. per sq. in. (Figs. 16 and 17). This was found to be the most economical way to house such a generator while still maintaining the electrical clearances described. The Washington generator has followed this design but local boiler codes limit the pressure to 60 lb. per sq. in. so that with dimension of 37 ft. diameter and length of 55 ft. the maximum operating voltage is expected to be lower. It is hoped that these differences in dimensions and maximum pressures will help to clarify the pressure-distance spark-over function which has been found to be less than linear

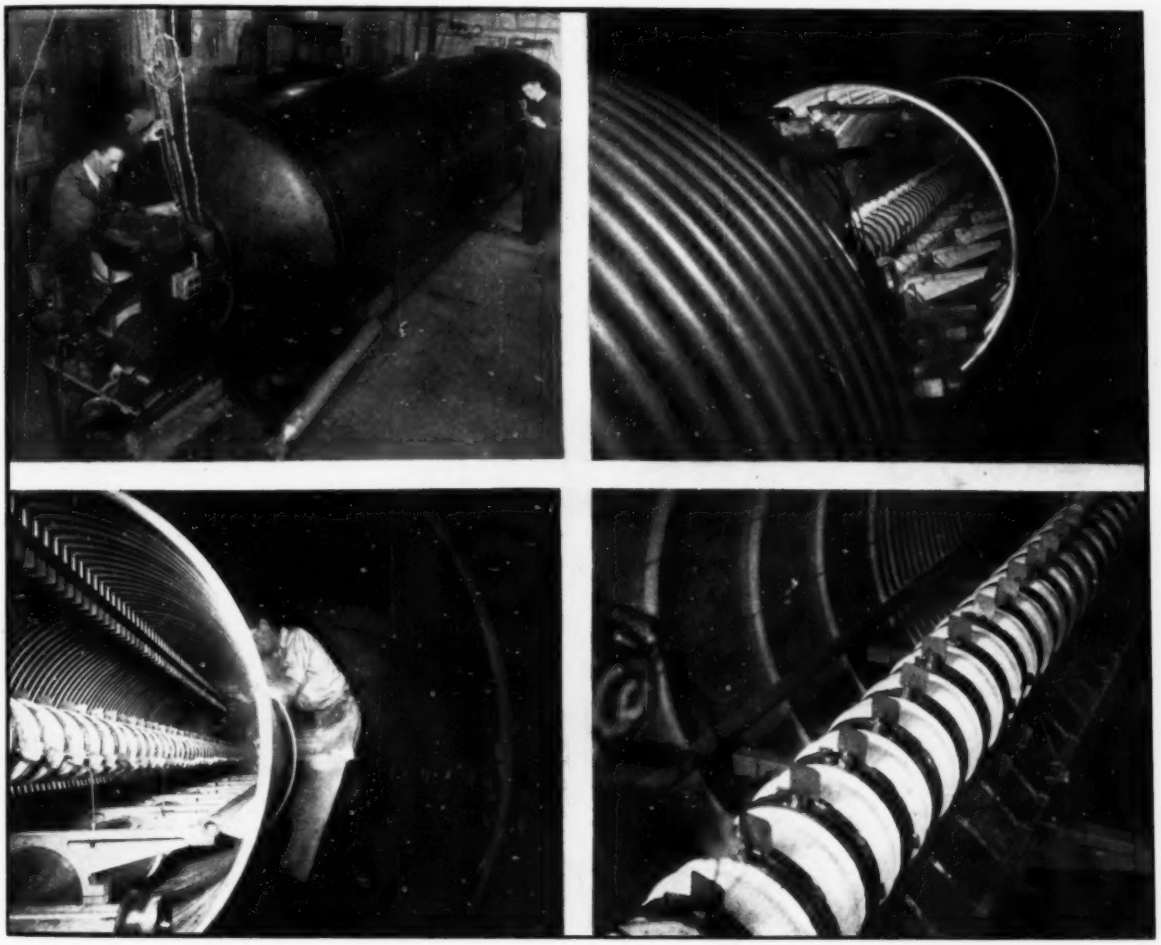


FIG. 16. Views of 2.4 million volts machine operating at 100 lb. per sq. in. air pressure at University of Wisconsin.

with pressure by Herb with the Wisconsin generator dimensions. Both generators are thus quite similar in electrical design but differ in mechanical design used in the construction.

The generator being constructed at the University of Minnesota is housed in a cylindrical container with hemispherical ends of diameter 18 ft. and length 33 ft., to operate at 100 lb. per sq. in. The internal electrical design is quite similar to the aforementioned ones with individual differences in the mechanical design.

Work with electronegative vapors[18] such as CCl_4, CCl_2F_2 mixed with air indicates that there is a large gain in breakdown strength for lower total pressures in some cases. This gain is not such a large factor, however, when total pressures of 80 to 120 lb. per sq. in. are used. Results in other laboratories with small gaps give a larger factor of gain than that at Wisconsin.

Use has been made in a number of laboratories of x-ray vacuum rectifier outfits of a few hundred kilovolts to accelerate beams of ions and a considerable amount of useful information about nuclear reactions has been obtained[19] of which references to the first results showing the apparatus used are given here. These and similar low voltage equipments have been very useful in giving accurate voltage efficiency functions of reactions with Li, B, Be as targets for different incident particles.

Still another method of accelerating particles was undertaken by Brasch and Lange[20] in 1927 and reported in 1931. They first showed that it was possible to obtain voltages of the order of 8 to 15 Mev measured by spark distances at Mt. Generoso in the Swiss Alps. They then devoted their attention to methods of making an accelerating tube along the multiple cascade tube principle. They set up an impulse generator by using the Marx circuit,[21] which consists in charging a set of condensers in parallel through resistances and allowing them to discharge through gaps in series. Their tube consisted of a series of metal plates with central holes spaced by flat insulators which serve to give a capacity distribution of voltage for impulses, while the holes in the metal plates function as electrical focusing lenses, as do the gaps between cylinders in the tube developed by the Carnegie Institution of Washington group. They attain pro-

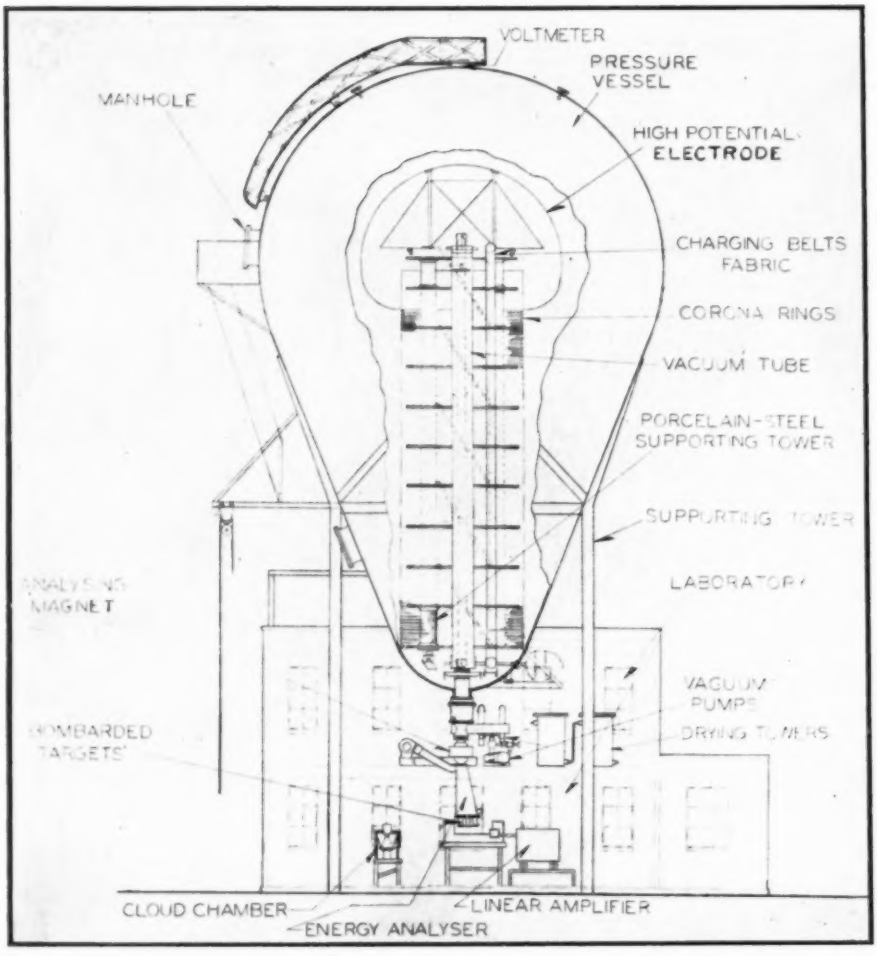


FIG. 17. Diagram of pressure generator under construction at Westinghouse Research Laboratories.

FIG. 18. Internal view of central vacuum tube and procelain support tower of Westinghouse generator. View through lower manhole showing central accelerating tube, porcelain-steel support column, corona rays, one pulley drive and belt.

tons of 1 Mev energy and by accelerating electrons, are able to produce x-rays of 2 Mev energy when using the impulse generator under oil.

A further development of this impulse generator operating in air under pressure has given particles of 3 Mev in a tank 10 ft. in length by 5 ft. in diameter,[22] which indicates that this method may be developed more extensively in the future. Such impulses of particles suffer from the same limitation as the original Tesla coil experiments, as the short on-time is such that it is very difficult to determine the nuclear reactions involved except by using a Wilson cloud in synchronism which reduces the number of observable disintegrations to a very small number.

It is expected that one of the possible limitations to Van de Graaff belt machines, such as the Westinghouse and Carnegie Institution developments, may be the limitation of belt insulator length, inasmuch as both of these are constructed with flanged porcelain insulators to support the high voltage terminals, in contrast to previous designs using Bakelite-type materials. If this is the case, there is already available a development which can be modified to use under pressure which consists in blowing an air stream containing small particles of charged siliceous material from ground to the high voltage electrode.[23] This is accomplished by passing the particle laden air through an ionizing region, as is done in the Cottrell method of electrical smoke precipitation, and removing this charge by a metal collector at the high voltage terminal. Results so far indicate that currents are obtainable which compare with those possible with belts, and it would seem possible to use the air stream at any required pressure for breakdown strength, since it must of necessity be in a separate column. Hollow support bushings for the high voltage terminals are available, and will serve this function readily.

Another line of attack in accelerating charged particles by repeated voltages, is that of applying voltages to a linear line of cylindrical coaxial electrodes so that the correct voltage is applied over a gap in synchronism with the arrival of the charged particle while changes in voltages on the electrodes are made during the time the charge particle is well within the electrode. Such methods were developed early by Wideroe,[24] by Sloan and Lawrence, and their co-workers at the University of California, and by Beams and his co-workers at the University of Virginia.

The linear accelerator of Sloan and Coates makes use of a radiofrequency oscillator applied to a series of electrodes with spacing increasing as the ions gain velocity. They have been able to produce 2.8 Mev Hg^+ ions but did not produce any disintegrations. To produce ions such as protons or alpha-particles of the same energy requires that the line be impractically long to oscillate at a high radiofrequency. This is because of the high velocity of light and because of interelectrode capacity and capacity to ground when using any of the available high frequency

FIG. 19. A view of the new electrostatic generator at the University of Minnesota.

power oscillators. Kinsey has applied this method to lithium ions, by using a few accelerating gaps bombarding hydrogen, and observed the production of helium ions in the same reaction originally observed by Cockcroft and Walton.

Beams and his co-workers at the University of Virginia have succeeded in accelerating protons to over 1 Mev energy by applying the voltages developed by a pulse along an artificial transmission line loaded to give tuning with the time of arrival of the protons at the accelerating cylindrical gaps.

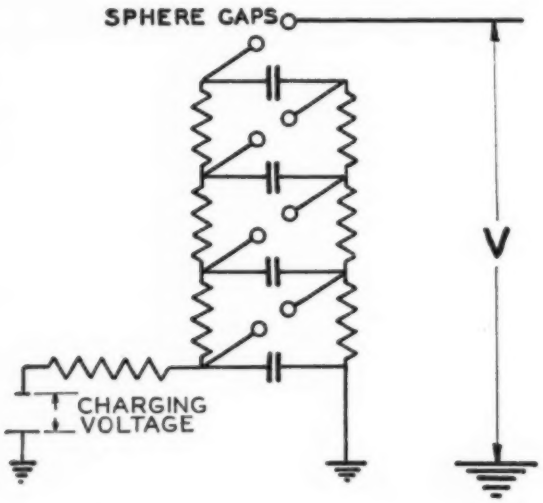


FIG. 20. Schematic diagram of impulse generator in which the condensers are charged in parallel through resistances until the spark gaps break down, thus discharging the condensers in series.

A method of obtaining electrons of high energy which has received considerable thought but which has not been reduced to practice as yet is that of using the induction e.m.f. due to changing magnetic field.[25] In accordance with Maxwell's equation

$$\text{Curl } E = -(1/c)(\partial H/\partial t),$$

where E and H are electric and magnetic field vectors. An electric field of around a volt per cm or less would be available to accelerated particles. In the designs so far proposed, there is difficulty in expecting an electron to remain in the central plane of the accelerating chamber as it is in unstable equilibrium, but this can probably be corrected by suitable application of auxiliary electric and magnetic fields. A more serious difficulty lies in the extremely long path required which is about 10^6 cm for 1 Mev electrons. Thus there would be required an extremely low vacuum to allow an electron to make the required number of circuits.

In conclusion, it can be seen that the methods for accelerating charged particles to high energies which have received the most successful development for nuclear transmutations are those of direct high voltage by means of belt machines as developed by Van de Graaff and the cyclotron method due to E. O. Lawrence. It is hoped, however, that a short historical summary of the developments in this field may lead to further effort on the other lines of attack which have not been explored as thoroughly as they undoubtedly will be in the future.

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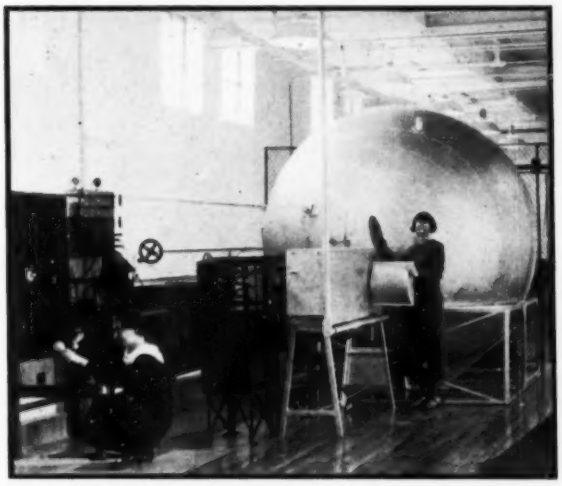
Resumés of Recent Research

Recent advances in experimental and theoretical physics are described in these columns in nontechnical language. It is intended that sufficient background be given to introduce the reader to the subject.

Photometry of Colored Light Sources

The measurement of the output of sources of highly colored light in terms of that of tungsten lamp standards by direct comparison is very difficult. This difficulty may be greatly reduced by the use of colored filters to overcome the color difference between the lamp studied and the standard. Another procedure for avoiding this difficulty is the use of the flicker photometer.

Two questions may be asked: Do these two methods give the same results for highly colored light, and are the results in keeping with the addition theorem and the standard I.C.I. values of the luminosity factors? Results obtained by twelve to sixteen experienced photometric observers, using these two methods, are given in the *Journal of the Optical Society*.* The sources measured were: high intensity mercury lamps, sodium lamps, neon lamps, and green, blue and pink fluorescent lamps. The observers' eyes were tested with the Ives yellow and blue solutions.



Ulbricht sphere with equipment for visual measurements.

The resulting Y/B ratio for all but one of the observers ranges from 91 to 113 percent (one observer 68 percent). The use of the flicker photometer was a new experience for most of the observers, but they soon learned to use this type of instrument so that they could make consistent readings.

*W. E. Forsythe, B. T. Barnes and Ann L. Shrider, J. O. S. A. **7**, 241 (1938).

The spectral intensity of the radiation from each source was measured and the luminous intensity was calculated by use of the standard I.C.I. luminosity factors. The results thus obtained agreed with the measured results within the experimental error of measuring such lamps. Several other tests were made such as the measurement of the relative luminosity of two mercury lines ($\lambda = 5461$ and 5780A), the measurement of the output of a mercury and a sodium lamp separately and together and the comparison of the measured and calculated results. All the tests made in this experiment are in agreement with the addition theorem and with calculated results using the I.C.I. luminosity factors.

Metallic Cohesion

From a knowledge of the energy of a metal as a function of volume, one may determine such things as the normal lattice constant, the heat of sublimation, and the compressibility. The first successful calculations of metallic binding were made by Wigner and Seitz for the monovalent metals, sodium and lithium. They showed that the valence electrons become detached from their atoms and form a "gas" of electrons in which the resulting ions float. The binding is due to the electrostatic attraction between the negative electrons and the positive ions.

In a recent article appearing in the *Journal of Chemical Physics*, Dr. J. Bardeen[1] discusses the compressibilities of the alkali metals and their variation with pressure. Calculations for lithium and sodium were made by a modification of the method used by Wigner and Seitz; for the remaining alkali metals, a cruder, semi-empirical method due to Fröhlich was employed. The calculated values of the compressibilities are compared with recent measurements of Bridgman which extend to pressures of about 45,000 atmospheres, and satisfactory agreement is obtained. This work provides a particularly sensitive test of the general quantum-mechanical theory of metallic cohesion.

The normal lattice constant of an alkali metal is determined not by the ionic sizes, as it is in the harder metals (e.g. Ni, Cu, Ag), but by the minimum in the energy of the valence electrons. The ionic volume is normally much smaller than the atomic volume in the metallic phase. At extremely high pressures, one might expect that the volume will be so much reduced that the ions will begin to touch one another, and in this case one may expect that the metal will take up a more close-packed structure (e.g. face-centered instead of body-centered). The metal for which the transition should take place at lowest pressure is C5, since it not only has the largest ion of the alkali metal but also has the highest compressibility. It is of interest in this connection to note that Bridgman has observed a polymorphic transition in C5 at a pressure of about 22,000 kg/cm^2, but none in the other alkali metals.

[1] J. Chem. Phys. **6**, 372 (1938).

Present-Day Design and Technique of the Cyclotron

A Description of the Methods and Application of the Cyclotron as Developed by Ernest O. Lawrence and his associates at the Radiation Laboratory, Berkeley

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READERS of the daily press have recently become acquainted with the word "cyclotron." They have become acquainted with it as an amazing tool whose applications seem to embrace a wide range of studies. The average reader is perhaps also a little amused at this latest toy of the scientist. The synonyms "atom-smasher" and "atom-whirligig" play into the hands of this amusement. His laughter rings hollow in his own ears when he reads further and discovers that a cyclotron is no mere toy, that it may weigh anywhere from 50 to 200 tons and may cost the institution which erects it many thousands of dollars, that a large proportion of the leading universities in the world are going to the expense of constructing such machines at the request of their most able physicists, chemists, biologists and medical doctors, that the trade of a "cyclotroneer" is one which has experienced no depression.

The advent of the cyclotron into physical research could almost have been predicted. The history of physics has been, since the time of Newton, one of steady progress in which certain fields of endeavor enjoy a popularity for a space of time. Physics turns from one subject of inquiry to the next logically; a subject retains its popularity only as long as it presents unsolved problems of a fundamental nature and at the same time offers the means for their solution. The duration of this popularity depends on a combination of many factors. One is the ease with which experiments can be conducted; another is the number of men engaged in work in this field; another is an indefinite factor depending on the number of men of genius fortune bestows on that period. Often it happens that a branch of physics will languish for many generations until some technique is established which enables precise work to be done on it.

Until almost the end of the nineteenth century the state of physics was such that experiments were easy, indeed they were usually performed at the physicist's own expense and in his own house. Here men were concerned with the physics of simple things, such as the laws of macroscopic mechanics, geometrical optics and the nature of heat. After the rapid upgrowth of laboratories in the last century, great progress was made in them which would have been impossible in the home laboratory. These strides were in what we may call a low force region. They were primarily studies of the extranuclear region of an atom. The discovery of radioactivity, in a way, came at a good time, for it, together with that of x-rays and the electron, stimulated interest in the atom for itself. It directly led the way to the nuclear model of the atom which has been such an intrepid guide through the jungles of extranuclear physics. These jungles are now well colonized and have good roads through them and although the brush is still thick in places, the general topography is well known.

With all that enormous progress there was parallel progress in the study of the nucleus. This was more a progress in techniques than

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facts because the worker in radioactivity had no gratings and echelons to give him eight-figure accuracy. Even today, one feels quite the blundering caveman beside one's spectroscopic brothers.

The discovery of radioactivity and the subsequent researches of Lord Rutherford exposed the nucleus to us under rather favorable conditions. The heavy radioactive elements have nuclei which are unstable; they obligingly give one some view of their secrets by tearing themselves apart before the eye of the fascinated physicist. This self-destruction of the radioactive atom demonstrated two things: that the nucleus is complicated and that it surrounds itself with an intense barrier of electrical force. The fact that only the heaviest elements are radioactive indicates that in all the other elements this barrier is something which must be pierced in order to understand the composition and building rules of a nucleus. It is clear that since extranuclear forces are measured in volts and nuclear forces in millions of volts that something extreme in the way of apparatus would be necessary for this work. This "something extreme" is the "atom-smasher," a generic term which includes many forms of apparatus, some of which are being described in another paper in this issue of the *Journal of Applied Physics.*

By the very nature of the hugeness and the costliness of the forces which a nuclear physicist must have at his command the tendency is less for him to work in stoical solitude and more for him to fraternize with others in centers which can be equipped to supply those forces. This is introducing a healthy competitive attitude among the younger nuclear physicists which is perhaps responsible for the enormous strides which have been made recently. These strides have not only been in the direction of elucidating the nucleus, but many by-products of the elucidation have shown themselves to be of untold value to other sciences. In a nuclear physics laboratory it is not unusual to find that "the boys" will consist not only of physicists but also of biologists, biochemists, medical doctors and engineers.

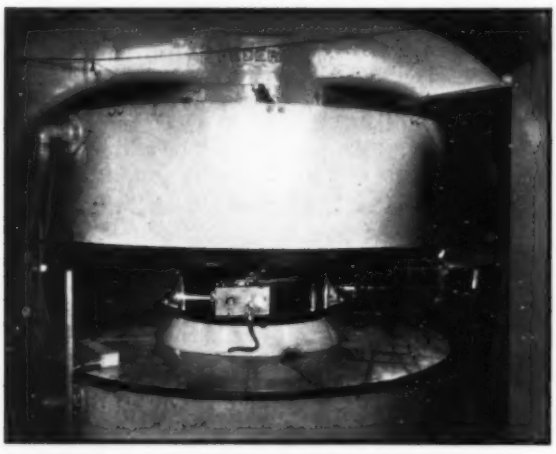

FIG. 1. A typical cyclotron. The instrument shown is the 37-inch one of the University of California at Berkeley.

The man in the street quite legitimately asks, "Why do people go to all this trouble, spend all this money on atom-smashers?" It is not our purpose to take up the bludgeon in defense of pure research but in a later section a little about the applications of the by-products of nuclear physics will be mentioned, and we think they will be eloquent enough.

I shall suppose that my readers are familiar with the fact that the only way we can learn anything about the nucleus is by making changes in it. They will know that these changes can only be produced by bombarding the nucleus with particles of the same general size, that in order to penetrate the nucleus the particle must have high velocity. The "atom-smasher" is simply a machine for giving such high velocities to small sub-atomic particles such as the proton, deuteron, neutron and alpha-particle. By measuring the energies of these projectiles and the energies of the fragments of the smashed atom together with the energies of any secondary disturbances, one gets the primary facts out of which an understanding of the structure of nuclei may be adduced.

The typical accelerating machine will consist of some source of ionized particles, some disposition of electrical fields to accelerate them and a chamber for studying the effects produced.

It has occurred to many people that the difficulties involved in handling extremely high voltages could be overstepped by using a small voltage several times over, by accelerating the particles not once but several times. It is to the credit of the experimental skill and determination

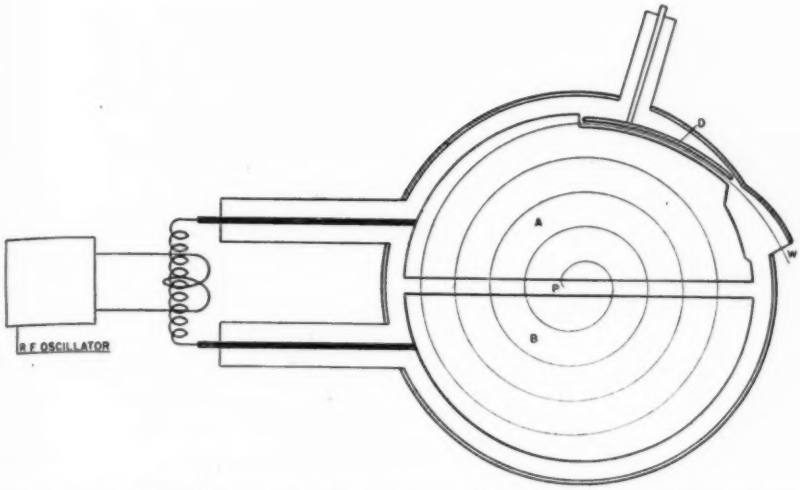

FIG. 2. A schematic section of the vacuum chamber of a cyclotron. An ion created at the center of the chamber moves in a spiral path under the joint influence of a rapidly alternating electric field between the two electrodes and a magnetic field perpendicular to the plane of the paper. The ion gains energy each time it crosses the gap between the electrodes, finally emerging from the vacuum chamber with very high speed. Diagram reproduced with permission of *General Electric Review*.

of Professor E. O. Lawrence of Berkeley that he saw this idea to a practical conclusion. Of several methods of multiple acceleration which Professor Lawrence and his associates tried, the one which is now embodied in the cyclotron has been the most successful. The preëminence of the cyclotron over other methods[2] tried by Lawrence's group is due to its flexibility and compactness, as well as the very high energies it can produce. The external appearance of a typical cyclotron is evident from Fig. 1 which shows the 37-inch instrument of the University of California at Berkeley.

The action of the cyclotron can best be understood by reference to Fig. 2, which is a diagram of the central portion of the cyclotron shorn of many of its essential, but at this stage, confusing details. This is a cross section of a flat circular box which is known as the "vacuum chamber" and which is placed between the poles of a large electromagnet, imagined here to be above and below the plane of the paper. Inside this box supported on glass insulators are two semicircular hollow electrodes called "dees." To these dees is connected a high power radiofrequency oscillator working at a frequency of between 8 and 15 megacycles. Above or below the center of the vacuum chamber is mounted a tungsten filament. The vacuum chamber is exhausted to a high vacuum and then a small quantity of some gas is allowed to flow into the vacuum chamber and out through the pump line. This raises the pressure in the chamber to something like 10^{-3} to 10^{-2} mm. The filament is maintained at a high enough negative potential so that electrons are forced off it into the gap between the dees. This stream of electrons ionizes the gas in that region and we may now follow the course of one of these ions under the influence of the magnetic and radiofrequency electrical fields. Suppose at the time the ion is created the uppermost dee in the figure is negative, the ion will be drawn toward it and therefore acquire a small velocity. With this velocity it will enter the practically field-free interior of the dee and under the influence of the magnetic field the path of this ion will be a small circle whose radius depends on the velocity of the ion, its charge, mass and the magnetic field. It is a very easy matter to prove that as long as the mass of the ion does not change, the time it takes an ion to describe a semicircle is independent of its velocity. Consequently, if the magnetic field is properly adjusted the ion will return to the dee gap just in time to discover that the electrical field has reversed. It will again be accelerated, travel in a slightly larger circle, and in the same elapsed time return to the dee gap for another acceleration. This goes on for perhaps a hundred times until the ion has reached the outer edge of the dee. Here it finds that a slot has been provided whereby the ion can pass into a region in which a transverse electrical field is maintained by a plate held in a high negative potential. This transverse field, called the deflecting field, together with the gradient of the magnetic field

[2] We are referring here to the linear resonance method, for which high voltages require very long glass tubes; to the adaptation of the Sloan x-ray tube, where the high voltage actually appears inside the vacuum chamber.

near the periphery of the chamber is sufficient to draw the ions away from the dees and direct them into a target chamber.

It is easy to work out the equations which govern the motion of ions in a cyclotron and to deduce the final energy from the dimensions of the apparatus and the working figures. Thus, for the ions to be in resonance the product of the magnetic field by the wave-length of the oscillators is constant. In obvious notation,

$$H\lambda = k.$$

If the ions accelerated are deuterons, $k = 394$, if they are alpha-particles k has the same value, if they are protons, $k = 187$—these numbers refer to H measured in kilo-oersteds, λ measured in meters. The energy depends on the dimensions of the apparatus and on either H or λ. If R is the radius of the final circle of ions, the energy expression assumes the simple form

$$E = cR^2/\lambda^2.$$

For deuterons c has the value of 24, for protons 12, and for alpha-particles 48. When R is measured in inches, λ in meters, E will then be given in millions of volts (Mv). From these equations we can see that since the electrostatic capacity of the dees is pretty well settled in the design, the lowest value of λ is thereby fixed. H is therefore also established and usually represents a value higher than the magnet can attain without overheating. A compromise must then be met in the design of the vacuum chamber and magnet which will give the limiting energy. Thus, for a cyclotron in which $R = 15$ inches, $\lambda = 26$ meters, the required magnetic field for resonance will be 15,150 oersteds for deuterons, and the energy will be about 8 Mv. With the oscillators which it is customary to use it is possible to get about 90,000 volts between the dees. Thus, the ions will acquire twice 90,000 or 180,000 volts per revolution so about 45 complete revolutions will be necessary before the ions emerge.

Under such operating conditions, a well-designed cyclotron will give forth a current in the neighborhood of 100 microamperes. This represents a power of 800 watts to be dissipated in the target.

If the cyclotron is filled with helium instead of deuterium it is possible to produce alpha-particles artificially. The alpha-particle beam "comes in" at a very slightly lower magnetic field but is very much weaker in intensity, since, in order to begin the beam, the helium atoms must be doubly ionized, a very inefficient process. Similarly, a proton beam of about the same magnitude as the deuteron beam "comes in" at about half the magnetic field. For the same λ and R the proton energy is half that of the deuteron energy and one-fourth that of the alpha-particle energy. Similarly, any heavier ions can be accelerated—after surmounting the difficulties of creating them in the first place. For some elements these are not great, and the hot spark seems to offer the greatest promise for metallic ions.

Constructional and Design Details

The magnet.—The magnet, since by its size it imposes a limit on the final output of the cyclotron, is an item which must be given the most careful consideration of all, both in design and in financing. One attempts at once to build as large a magnet as is feasible financially and consistent with practical limitations which we shall mention later, and also to build it to be as economical to run as possible. It is customary to make a rough guess as to the size of the vacuum chamber based on one's past experience, or the advice of others. Recently, theoretical investigations of the motion of ions in cyclotrons have been made by R. R. Wilson and M. E. Rose which give one a better basis on which to make these guesses.

The next step is usually to construct a scale model from which the behavior of the large magnet can be predicted. It can easily be shown that if the model is n times smaller than the proposed magnet a magnetomotive force of $1/n$th that in the big magnet will give the same B and H in the model as will be found in the big magnet. Thus measurements can be made at various places in the magnetic circuit which will give one an idea as to the magnitudes of the fringing flux and the approach to saturation of different parts of the magnet. It is desirable of course that the magnet should saturate uniformly, for in that case the homogeneity of the field in the gap will suffer the least change from low to high magnetic fields. Obviously, the more iron that

can be put into the magnet the lower the reluctance of the circuit and therefore the smaller the magnetomotive force for a given field.

The magnetomotive force is supplied by the copper coils, and here it may be shown that the product of the power in kw and the weight of copper in tons is proportional to the square of the ampere turns multiplied by the mean diameter of the coils. It is obvious here, too, that a saving in power can be accomplished by increasing the number of tons of copper and in a final design the initial cost of the iron and copper must be balanced against the costs of operation.

Other factors such as the deflection of the horizontal yokes under the attraction of the pole pieces, the heating of the copper coils at the current densities required, the mechanical forces on the coils due to the interaction of their currents with the fringing flux are elements of design which require consideration.

The vacuum chamber.—Between the poles of the magnet is placed a chamber which, with the exception of the top and bottom covers, is made of nonmagnetic material, a cross section of which is shown in Fig. 3. Most of these chambers have been made from a piece of brass sheet rolled into a circle and welded together. There has been a tendency of late to use castings entirely for these chambers. Castings have a tendency to be porous and despite the convenience which they present in allowing one more freedom of design, this porosity, the degree of which varies enormously from foundry to foundry, has caused many to adhere to the well-tried rolled ring structure. A photograph of the interior of the 37-inch cyclotron at the University of California at Berkeley is shown in Fig. 4.

Referring to Fig. 3 which shows the 37″ vacuum chamber at Berkeley, one sees that the dees are supported on Pyrex insulators, the vacuum joints of which are made with rubber gaskets and clamping rings. The means of adjusting the position of the dees is provided by a four-legged spider cast from lynite. The flexible

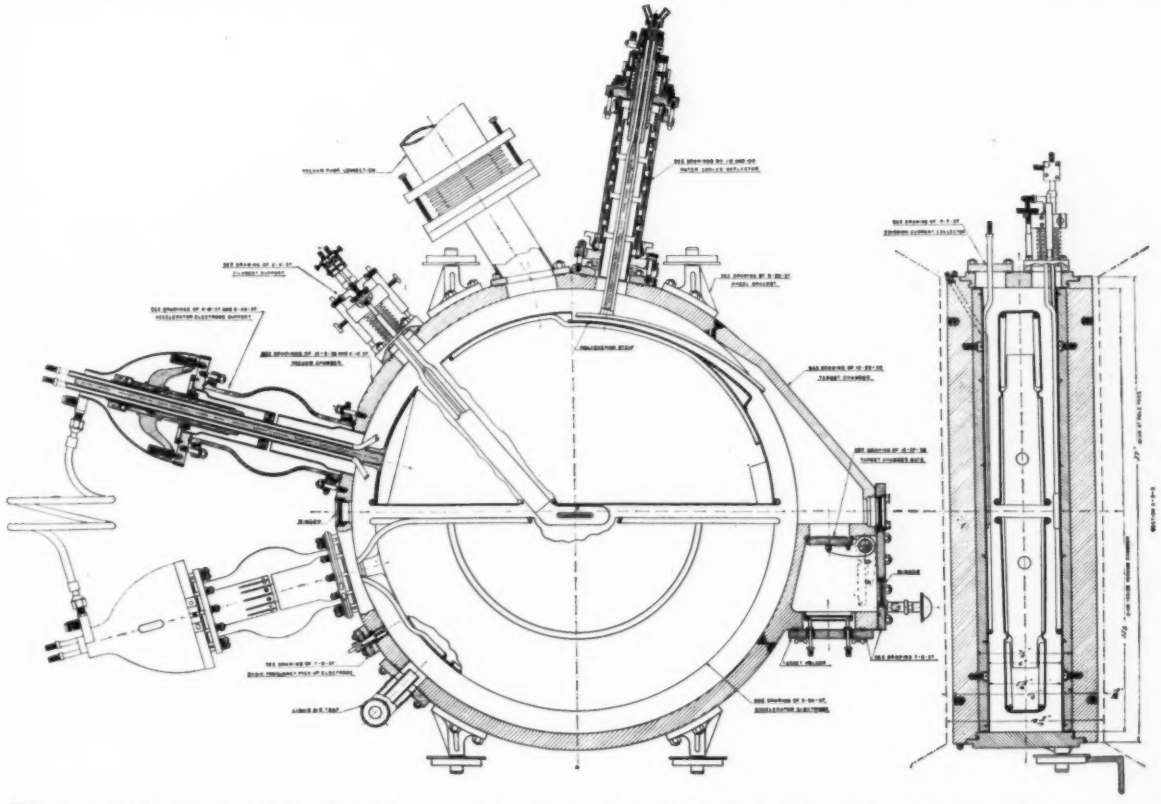

FIG. 3. A detail drawing of the 37-inch vacuum chamber of the smaller Berkeley cyclotron. Going around the edge of the chamber clockwise from the dee supports one encounters the following in order: the filament, the pump line, the deflector, a window, the vacuum gate for the target, the target orifice, the liquid-air trap, the *RF* probe. Notice, too, the wheel brackets which are removable and yet allow one to extract the chamber from between the poles of the magnet.

joint for this adjustment is simply a flat copper diaphragm fastened on one edge to the dee and on the other to the outer end-plate which bolts on to the Pyrex insulator. An attempt has been made in this design to give the radiofrequency currents a more natural path to the dee. In any assembly in which gaskets are used for the seal this must be done to avoid ruining them by radiofrequency hysteresis or by the heating of adjacent metal.

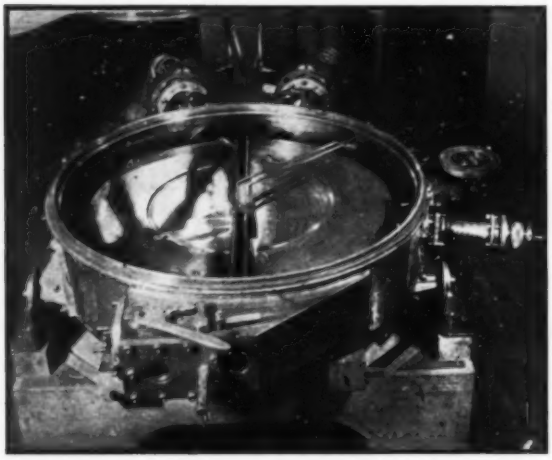

FIG. 4. Interior view of the 37-inch cyclotron at the University of California at Berkeley.

The form of inductance shown in this figure has been abandoned and of this we shall say more later. A running check of the voltage on the dees is provided by an insulated probe set in the wall of the chamber and connected to a small tuned amplifier. Somewhere on the chamber wall is to be found a liquid-air trap. These traps are conveniently made of metal with standard plumbing copper elbows and with a $\frac{1}{32}$-inch German silver tube as an insulator. By using a silver solder (Sil-fos or Phos-copper) these traps can be made guaranteeably leak-proof and extremely sturdy.

As large an orifice as possible is provided at some other convenient location for bolting on the pump-line. The deflector-insulator carrying the deflector plate through a hole in the tank wall is bolted on in the emerging quadrant. A standard 12″ length of commercial flanged 3″ Pyrex piping is an adequate insulator for voltages up to around 75,000, particularly if the voltage is distributed by a series of floating shields inside it. Provision must be made for adjusting the position of the deflector-plate. It is more convenient if the in and out and tilting motions can be made independent. For high current operation the deflector-plate must be cooled and the conductivity of water for these voltages makes the use of oil cooling more desirable. To prevent too much sputtering of metal from the copper deflecting-plate it has been found that by chromium-plating it this can be cut down, at least where the deflector-arm passes through the Pyrex insulator. Inside the tank, sputtering from the dees and tank wall onto the deflector soon coats the chromium with a layer of copper so that its efficacy is lost.

The dees can be built up in a variety of ways, one of the best of which is to make them from pie-plate shaped spinnings using the copper water-cooling tubes as a skeleton support. The beam in emerging always strikes the exit-lip of the dee to a greater or lesser extent depending on the adjustment of the cyclotron. It is clearly desirable that this should be minimized but it is nearly impossible to reduce it to zero. Consequently, the emerging lip is made from a piece of thin molybdenum carried in grooves and slit so as to be perfectly free. One is hereby trying to avoid the buckling of the lip by its expansion when heated by the beam. At the highest currents to which the cyclotron has been pushed the molybdenum strip has been kept from buckling by the release of constraints and slitting mentioned above.

The target chamber requires particular attention since for routine operations it is essential that the time spent in changing targets be minimized. For that reason a vacuum gate is provided whereby the target chamber can be isolated from the main cyclotron vacuum and, after a target has been changed, pumped down with a mechanical pump. The pressure can be reduced in a few minutes so that opening the gate will not "stall" the diffusion pumps. High intensity bombardments are usually carried out in a "bell-jar" window. This consists of a structure containing a window (0.001 inches aluminum) isolating the cyclotron vacuum from a region filled with a neutral gas (helium or hydrogen) at a few cm pressure. The beam passing through the window and gas strikes the

target. The presence of gas is necessary to assure cooling of the surface of the window and target and to prevent the target from going to pieces. In the eventual failure of a window no harm is done to the filament inside the cyclotron by this practice.

The filament which creates the ions initially is mounted on the end of an adjustable arm, and consists of a hairpin of tungsten clamped to water-cooled leads and surrounded by a water-cooled shield. To prevent the filament from being shaken to pieces it is heated with high frequency current (200 kc). Electrons are driven off it by an emission voltage of several hundred volts applied directly to the filament. The magnetic field collimates this electron beam into a vertical sheet which falls on a separate water-cooled plate whose function is to protect the upper lid of the vacuum chamber.

Since the voltage between dees has a peak value of as high as 90,000 volts and since the voltage on the deflector is in the neighborhood of 70,000 volts, it is clear that discharges will pass between these electrodes and the chamber under occasional adverse conditions, such as during the first few moments of operation after a shut-down. The resulting gas bursts overload both the radiofrequency supply and the deflector supply and so stop the operation of the cyclotron. These interruptions can be minimized by increasing the pumping speed of the pumps. In the 37-inch cyclotron a pumping speed of about 100 liters per second has been found to be about adequate. Several features of interest were incorporated in this pumping system, which consists of a number of low speed pumps in tandem. To stop the back-wash of oil vapor into the vacuum chamber a large carbon dioxide-acetone trap was placed near the pumps. About 100 pounds of dry ice per week was found to be necessary to keep the trap cold all the time. Between the pumps and the cyclotron was a vacuum gate so that the vacuum chamber could be opened to air without any delay to let the pumps cool down. This gate also served to reduce the pumping speed after the tank has been "cleaned up." A mechanical pump was provided for the rapid exhaust of the tank preparatory to opening this gate after such an opening.

Throughout the whole system rubber gaskets are used to make vacuum joints. In the pumping system Neoprene was used because of its resistance to oil, elsewhere pure gum sulphur-free rubber is to be preferred. Instead of stop-cocks, steam valves rebuilt as suggested by J. W. M. DuMond are used.

It may be noticed that one side of the vacuum chamber has been kept free from appurtenances. The purpose of this is to allow space for an auxiliary tube through which the beam can be conducted far away from the cyclotron. For many experiments in physics it is essential to work in a region less crowded than that adjacent to the vacuum chamber, away from the magnetic field and from the large neutron background of the cyclotron. The beam in emerging from the vacuum chamber cuts across the peripheral gradient of the magnetic field and therefore diverges. In order to conduct the beam down such a tube it is necessary to refocus it. Fortunately, the beam clings close enough to the vacuum chamber so that additional iron may be bolted to the side of the magnet, short-circuiting

FIG. 5. Resonant line used to supply the high frequency voltage to the dees. The cyclotron shown is that at Columbia University. Courtesy of *Science Service*.

some of the flux. This iron can be made of such a shape as to refocus the beam at the end of the tube.

If one plots a graph of the number of microamperes of the beam against the voltage between the dees he finds this is a rapidly increasing function. It is desirable therefore to attain as high a voltage as possible between the dees. The square of this voltage can be shown to be proportional to the power in the dee circuit, the Q of this circuit and inversely proportional to the frequency and to the capacity of the dees. This relationship is familiar to every amateur radio operator who knows that since Q depends only on design, it is the point from which an effort to increase the dee voltage should be begun. Q is simply the ratio of $\omega(=2\pi f$, where f is the frequency) times L (the total inductance of the circuit) to R, where R is the radiofrequency resistance of the circuit. An approximate formula for R which is valid in this region and for cylindrical conductors is $R=f^{\frac{1}{2}}/d$. When f is in megacycles and d (diameter) is in inches, this gives R in ohms per thousand feet. Clearly then, since the capacity and inductance are fixed by the dimensions of the cyclotron and the resonance relation, attempts to improve the voltage between dees at constant power must be directed toward reducing R. This can be done by using as an inductance not the coil made of small diameter tubing shown in Fig. 2 but a "coil" made from lengths of large diameter copper pipe. The Berkeley cyclotron is now using 3-inch diameter pipe, and indications are that even larger diameters would be preferable.

The Pyrex insulators which were mentioned earlier are called upon to support a very large torque, because of the great weight of the dees. At the same time they are under extreme stress from the large radiofrequency electric fields which cause considerable dielectric hysteresis. The resultant heating necessitates their being cooled by strong air blast. Even so, the glass sometimes becomes conducting through heating, sputtering, and other causes which immediately allows large eddy currents to flow. The destruction of the insulator is then assured. To obviate this difficulty the possibility of supplying the dee voltage, by supporting them on the ends of long heavy copper tubes mounted in a metal envelope and connected together so that their effective length constitutes a resonant line, has been suggested. This is simply a quarter-wave line with lumped capacity. The radiofrequency voltage is then applied to this line at points near the shorted (and grounded) end. It is a property of quarter-wave lines that the shorted and grounded end is a voltage node and that the open end is a voltage loop. Consequently, if the oscillator voltage is properly applied to the resonance system through an insulator, the insulator will be called upon to bear the electrical stresses consistent with this low voltage (10,000 to 15,000 volts). The voltage on the dees then corresponds to the loop of the quarter-wave line and will amount to, say, 100,000 volts. This scheme is actually being tried by Dunning at Columbia (Fig. 5) and is being contemplated for the 60-inch cyclotron in Berkeley.

The oscillator.—Supplying the radiofrequency voltage to the dees is a matter offering a range of possibilities. Since powers of the order of 30 to 50 kw and even more are required in general, the oscillator must be very ruggedly built. Commercial tubes are available for such powers but they are very expensive. As a result many prefer to build their own tubes because of the ease with which repairs can be made. Such tubes are not difficult to build and seem to be as satisfactory as commercial tubes even under the adverse treatment they are sometimes called upon to withstand. Homemade tubes are kept continuously on the pumps and, if soundly built, require almost no attention. A self-excited oscillator is the simplest to build and can be made to give very satisfactory performance. It is still somewhat of a question whether the expense of a crystal-controlled oscillator is justified. Each arrangement has its own staunch adherents. Of the plate power, which may be as much as 5 amperes at 10,000 volts (three-phase full-wave), over half is lost in the anodes of the tubes themselves while most of the rest is dissipated as heat in the covers and walls and other adjoining metal of the cyclotron vacuum chamber. Wilson has recently shown that in the Berkeley cyclotron several hundred microamperes of high speed ions are circulating inside the cyclotron and never appear as emergent beam. This "phantom beam" has been put to good use because it has been

found possible to insert targets between the dees and subject them to intense bombardment without reducing the emergent beam. The power load represented by this "phantom" is about 7 kw whereas the emerging beam constitutes in the neighborhood of 1 kw.

Shielding and other matters.—The neutron yield at high currents and voltages from a cyclotron is colossal. It is imperative that all workers be required to carry pocket ionization chambers at all times. As an added safeguard to the health of workers frequent blood counts should be required.

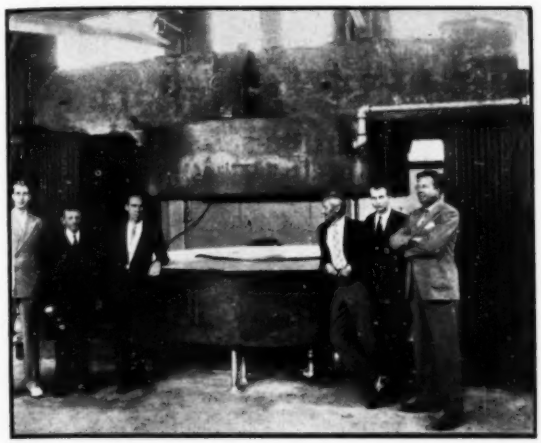

FIG. 6. The enormous magnet of the new 60-inch cyclotron now being built at the University of California at Berkeley.

The intensity of the neutrons can easily be reduced by surrounding the apparatus with a wall of water two or three feet thick, made either from large tanks or by stacking up ordinary rectangular five-gallon oil cans filled with water.

The controls may be placed at some distance from the cyclotron in order to reduce the exposure of the operator to stray neutrons and to allow for ready accessibility to the cyclotron. Efficiency is increased if the operator has complete knowledge of the behavior of all parts of the apparatus. The well-laid-out control circuit will be sufficiently interlocked so that the chances of damage to the cyclotron are minimized. In the event of some failure, such as stoppage in a cooling pipe, the circuits which are influenced by this failure should automatically cut off and a pilot light indicates the trouble. All the necessary meters should be at the control desk so that the operator may notice any abnormalities which often presage a breakdown. It is desirable to limit the number of manual controls as much as possible and to simplify the panels so that relatively unskilled men can operate it, full of the confidence that they can do no damage. These remarks, of course, apply only to cyclotrons which are being called upon to adhere to long bombardment schedules. A cyclotron which is used intermittently requires no such elaborate facilities. However, the small proportion of cyclotron hours which are available makes such facilities almost necessary.

Focusing of the ion beam.—The description of the operation of a cyclotron which has been given above was of course oversimplified. It has been assumed there that the magnetic field is quite uniform and that the electrostatic fields do not penetrate within the dees. It was pointed out in Lawrence's original paper that the departures from these conditions were responsible for focusing effects which tended to hold the beam together. Recently, these effects have been studied independently by Wilson and by Rose. They have shown that, since the electrostatic fields do penetrate the dees, the effect of this curvature of the electrostatic lines of force leads to focusing for small energies, but that this effect becomes rapidly smaller at increasing radii and is replaced by a magnetic focusing because of the decreasing magnitude of the magnetic field toward the periphery. Wilson showed experimentally that in the 27-inch cyclotron in Berkeley the beam was confined within limits which agreed very closely with his calculations. It has further been shown that the difficulty of devising a magnetic field which will lead to strong focusing at high energies and also preserve the resonance relation suggests the existence of an upper limit to the energy which can be obtained with present designs. This upper limit as given by Rose is about 20 million volts for deuterons, considerably above that contemplated for any cyclotrons now under construction.

The cyclotron's bounties.—The mere recitation of numbers does very little to convey an impression to a reader who has not had practical acquaintance with their significance. Yet, to the nuclear physicist it is just these numbers which constitute the cyclotron's best advertising matter

and which are making him feel the strong necessity of it for nuclear physics. The great range of applications to which cyclotrons have already been put has led important institutions all over the world to construct them. There can be no question of faddishness about this to anyone who has seen the demands placed on the 37-inch cyclotron at Berkeley. There, during recent months it has been necessary to run the cyclotron something like 22 hours a day every day in order to supply the needs of the physicists as well as the biologists, chemists and medical men who have realized the possibilities of the techniques it has made available for them. Cyclotrons are already in operation in Berkeley, Cornell, Princeton, Michigan, Illinois, Rochester, The Bartol Institute, Tokyo, and Leningrad. All but three of these are of comparable size to the 37-inch cyclotron in Berkeley. The new 60-inch cyclotron now being built at Berkeley is shown in Fig. 6. The beauty of an emerging ion beam is shown in Fig. 7 which is from the cyclotron of the University of Michigan. At Berkeley, Yale, Harvard, Chicago, Columbia, Purdue, M. I. T., Ohio

FIG. 7. An emerging ion beam. The cyclotron shown is the one at the University of Michigan.

State, Washington, Indiana, Liverpool, Cambridge, Paris, Copenhagen, and McGill cyclotrons, for the most part of larger dimensions, are under construction. This list is probably incomplete.

The ease with which voltages far in excess of those of other methods can be attained is the prime factor leading to this great building program. The work so far accomplished with the cyclotron has been mainly exploratory and, with every increase of energy and current, workers have found new phenomena disclosed to them, have seen barely observable effects acquire enough intensity to allow precise measurements to be made of them. The vast bulk of the work to date has been in investigating artificial radioactivity. More new isotopes have been made artificially than there are stable ones in nature. The work of ascertaining the energy changes involved in this alchemy has hardly been begun. The character of the radiations emitted from these artificial substances is only roughly known in a few cases. A great amount of good work has, of course, been done for the lighter elements but the major part of the periodic table is still to be unraveled. At 8 million volts radioactive isotopes can be produced throughout the periodic table but intensities toward the upper end are still weak for many of them. No one has dared imagine publicly how far off the line of stability we may be able to go at higher voltages, nor has he ventured to predict the complicated, perhaps many-bodied reactions which will occur with these more energetic projectiles. It is safe to say that nuclear physics is in very much the stage of development that extranuclear physics was in at the time of Fraunhofer.

The by-products of nuclear physics have opened to biology and chemistry fields of equal magnitude. The clinical study of the action of neutron rays is still to be made. It is established in many cases that their action is quite different from that of x-rays. Since the type of ionization in a cell is characterized in the case of neutrons by the very dense ion cloud of a projected proton and in the case of x-rays and radium by the sparse ion cluster of a recoil electron, it is to be expected that the biological activity per unit of ionization will be quite different in the two cases. Indeed, in the few examples which have been studied, this is so. There is some indication in the experiments of John Lawrence and others that the differential effect of neutrons on malignant and healthy tissue is more favorable than in the case of x-rays. With the large neutron yields now available it has been found possible to collimate neutron beams of sufficient intensity to do cross-fire radiation on larger animals such as rabbits and sheep. The 60-inch cyclotron in Berkeley is being built with the idea of making these experi-

ments easier through the higher intensities it will give.

We have spoken above of the great number of artificial radioactive substances which can be produced. These substances differ in no chemical way from the normal, stable atoms of which they are isotopes. They differ physically, however, in that they emit either beta- or gamma-rays and so can easily be detected in exceedingly minute quantities by a variety of instruments. This fact has been utilized by chemists to investigate reaction rates, photosynthesis and many other problems. This sort of study can be made quantitatively with great accuracy.

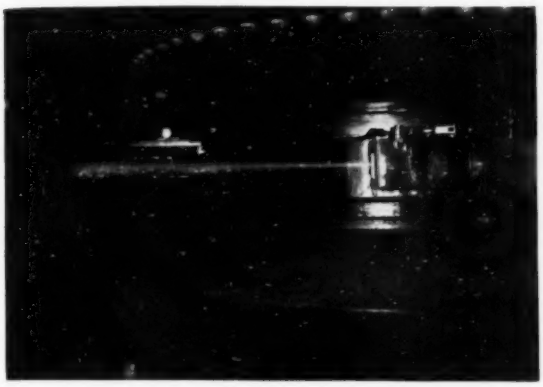

FIG. 8. An emerging ion beam from the cyclotron of the Biochemical Research Foundation which is located at the Bartol Research Foundation. The beam is of 9.7 Mev deuterons and the length is approximately 60 cm. The intensity of the beam is approximately 1 microampere.

In biology problems of metabolism, rate of circulation and interconversion of body fluids can again be studied quantitatively. For example, the destination of the different constituents of a meal under various conditions can be completely ascertained. Further enumeration of the problems afforded an easy and exact solution would be pointless since no biologist will have difficulty in thinking of hundreds of them.

I have tried in this article to give some conception of the detail of a cyclotron and to indicate very briefly the essential role it plays in all of the natural sciences. It is impossible in a paper of this scope to do adequate justice to either of these topics.

I want to express my deepest gratitude to Professor Ernest O. Lawrence, Director of the Radiation Laboratory, Berkeley, and to Dr. Donald Cooksey, Assistant Director, for the opportunities my long stay in their laboratory afforded. Acknowledgment must be made to the large number of men there whose untiring labors and inspiration have done so much to bring the cyclotron to its present high state of development. In particular, I should like to mention Professor M. Stanley Livingston, Professor Edwin McMillan, Dr. S. N. VanVoorhis, Dr. A. H. Snell and Mr. William Brobeck who, together with the Directors, have been outstanding in their contributions.

Here and There

New Appointments and Promotions

Dr. Gordon M. Shrum, Professor of Physics at the University of British Columbia, has been appointed Head of the Department.

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Horace T. Herrick has been appointed an Assistant Chief of the Bureau of Chemistry and Soils. Mr. Herrick will assume responsibility, on behalf of the Department of Agriculture, for the general direction and coordination of the chemical and chemical engineering investigations of the four regional research laboratories authorized in the Agricultural Adjustment Act of 1938 to conduct researches into and to develop new scientific, chemical and technical uses for farm products and by-products.

★

Science reports the following new appointments:

M. Jean Perrin, Professor of Physics in the University of Paris and a member of the council of the University, has been appointed by the French government President of the High Committee for Scientific Research. M. Perrin received the Nobel Prize in physics in 1926.

Dr. Robert Serber, formerly Research Associate at the University of California at Berkeley, has been appointed Assistant Professor in the Department of Physics at the University of Illinois. Since the death of Dr. Kunz on July 18, Dr. P. Gerald Kruger has been acting Head of the Department.

Dr. Lester T. Earls, of Centenary College, has been appointed Assistant Professor of Physics at the Iowa State College.

Dr. W. H. George, Lecturer in Physics at the University College, Southampton, has been appointed Head of the Department of Physics at Chelsea Polytechnic, in succession to Dr. L. Lownds, who is retiring after thirty-seven years' service.

Julian Glasser has joined the staff of Battelle Memorial Institute at Columbus, Ohio, and is engaged in chemical and electrochemical research in the field of metallurgy. Dr. Glasser has had industrial experience as electrochemist with the Utah Radio Products Company and as physical chemist with the General Electric Company.

Nature states that a new Institute for Atomic Physics has been inaugurated at the Royal Hungarian University for Technical and Economic Sciences, and Professor Z. Bay, formerly Professor of Theoretical Physics in the University of Szeged, at present Director of the Tungsram Research Laboratory of the United Incandescent Lamp and Electrical Company, has been appointed the first Professor of Atomic Physics.

★

The honorary doctorate of laws will be conferred on Sir Walter Langdon Brown, Emeritus Professor of Physics at the University of Cambridge, on the occasion of the centenary of Dalhousie University, Halifax, Nova Scotia.

★

The honorary doctorate of the University of Cologne has been conferred on Dr. W. L. Bragg, Cavendish Professor of Experimental Physics at the University of Cambridge, formerly Director of the National Physical Laboratory.

★

Sir Arthur Eddington was elected President of the International Astronomical Union at the sixth triennial meeting held at Stockholm from August 3 to 10. He succeeds Professor Ernest Esclangon, Director of the Paris and Meudon Observatories. The next meeting of the union will be held in Switzerland in 1941.

★

According to *Nature*, Professor C. D. Ellis, who holds the Wheatstone Chair of Physics at Kings' College, London, has been granted leave of absence for the Michaelmas and Lent terms in order to make a tour which has been arranged by the Conference of Canadian Universities. Professor Ellis plans to spend some time, up to a week or ten days, in most of the universities, in order to have ample opportunity for meeting the staff and for discussing matters of interest. He is leaving England in September, and will go first to Vancouver, and will visit Edmonton, Saskatoon, Winnipeg, Ottawa and Montreal before Christmas. Starting again in January, he will visit Hamilton, London, Toronto, Kingston, Quebec, Sackville, Halifax, returning to England at the end of March.

★

Canadian Research Scholarships

Forty-nine scholarships have been awarded for 1938–1939 by the National Research Council of Canada. Twelve candidates will work in physics, including three in the National Research Laboratories.

Upper New York State Section of the A. P. S.

The fall meeting of the Upper New York State Section of the American Physical Society will be held at the Physics Department of the University of Rochester on Saturday, November 5. The program will be as follows:

Color Photography. C. E. K. MEES, *Eastman Kodak Company*
Thermometers. BRADFORD NOYES, *Taylor Instrument Company*
Mechanism of Fluorescence. SAUL DUSHMAN, *General Electric Company, Schenectady*
Preparation for College Physics. BRIAN O'BRIEN, *University of Rochester*
The Cyclotron. L. A. DUBRIDGE, *University of Rochester*

The Taylor Instrument Company, the Eastman Kodak Company and Bausch and Lomb Optical Company will be glad to receive visitors at their plants on Friday, November 4. The plants will not be open on Saturday. Further information concerning the meeting may be obtained from Henry F. Kurtz, Bausch and Lomb Optical Company, Rochester, New York.

★

Metropolitan Section of the A. P. S.

The first meeting of the Metropolitan Section of the American Physical Society for the season 1938–1939 will be held on Friday, November 4th, in the Pupin Physics Laboratories of Columbia University in New York City. The program will be as follows:

Afternoon Session—4:00 P.M.

The Properties of Gases at Low Temperatures. G. E. UHLENBECK
The Order-Disorder Transformations in Alloys. F. C. NIX

Evening Session—8:00 P.M.

The Separation of the Isotopes of Nitrogen. H. C. UREY

★

American Astronomical Society Meeting

The sixtieth meeting of the American Astronomical Society was held at the University of Michigan from September 14 to 16, under the presidency of Dr. Robert G. Aitken, Director Emeritus of the Lick Observatory. The address of welcome was given by Dr. Alexander G. Ruthven, President of the University. The annual dinner was held on Friday evening at seven o'clock at the Michigan Union. On Saturday morning there was an inspection of the McMath-Hulbert Observatory and of the motion pictures of recent solar prominences. After the close of the meeting there was an excursion to Henry Ford's Greenfield village.

★

International Union of Geodesy and Geophysics

The President of the United States has invited the International Union of Geodesy and Geophysics to hold its seventh general assembly in the United States in 1939. The invitations have been extended on behalf of the President by the Department of State through its diplomatic missions to the governments to which these missions are accredited, and invite the participating countries to be represented by delegates on this occasion.

It is planned to hold this seventh triennial assembly of the Union in Washington, September 4–15, 1939, according to a statement made by Dr. John A. Fleming, Director of the Carnegie Institution's Department of Terrestrial Magnetism, who is General Secretary of the American Geophysical Union. The American Geophysical Union is the American Section of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The Council is collaborating with the American Geophysical Union as host to the assembly. The last general assembly of the International Union was held at Edinburgh, Scotland, in September 1936.

The 35 nations at present adhering to the International Union are: Argentina, Belgium, Brazil, Bulgaria, Canada, Colombia, Chile, Czechoslovakia, Denmark, Egypt, Finland, France, Germany, Great Britain, Greece, Holland, Hungary, Indo-China, Italy, Japan, Morocco, Mexico, New Zealand, Norway, Peru, Poland, Portugal, Rumania, Siam, Spain, Sweden, Switzerland, Union of Soviet Socialist Republics, United States, and Yugoslavia.

★

Sir Richard Gregory's Lecture before the Carnegie Institution of Washington

The Carnegie Institution of Washington announces that Sir Richard Gregory, distinguished English scientist, has accepted an invitation to deliver the next Elihu Root lecture at the institution's auditorium, Washington, D.C., on the evening of December 8. Sir Richard Gregory has come into position of prominence and of great influence through the books he has written, the addresses he has delivered, and most of all through his brilliant editorship of *Nature*, an English journal which has become an international clearing house for preliminary announcement of scientific researches and results.

★

Necrology

Dr. A. E. H. Tutton, whose work stands as an enduring contribution to chemistry and crystallography, died on July 14.

★

By the recent death of Dr. Charles-Edouard Guillaume the world is deprived of a distinguished man of science who had taken a leading part in the advancement of the subject which, for more than fifty years, he had made his own. In 1920 he was awarded the Nobel Prize for physics for his work on the nickel-iron alloys.

★

Professor Jakob Kunz, Professor of Mathematical Physics in the University of Illinois, known for his work in astrophysics, died on July 18, aged sixty-four years.

★

Dr. Thomas C. Hebb, Professor and Head of the Department of Physics at the University of British Columbia, died on August 13 at the age of fifty-nine years. He had been connected with the university since 1916.

Contributors to This Issue

William H. Wells received his A.B. degree from Amherst College in 1928 and his Ph.D. from Johns Hopkins University in 1934. In 1933–34 he was physicist at the Department of Terrestrial Magnetism, Carnegie Institution, Washington. In 1934–36, he was research fellow at the University of Minnesota, and from 1936– research physicist at the Westinghouse Research Laboratories, designing the large electrostatic generator.

Franz N. D. Kurie was born in Colorado in 1907; B.Sc. from McGill, 1927; Ph.D. from Yale, 1932. In the latter university he did research in the field of radioactivity as a graduate student, and later as Sterling Fellow. As National Research Fellow, he went to the University of California where he became involved in nuclear physics under Professor E. O. Lawrence, and for the last five years there, has been intimately connected with the development of the cyclotron. He is now at Indiana University as Assistant Professor, where a large cyclotron is to be built under his direction.

Alexander Goetz was born in 1897 in Wiesbaden, Germany. He studied civil engineering at the Technische Hochschule, Darmstadt, and physics and mathematics at the Universities of Freiburg and Göttingen, receiving his Ph.D. from the latter institution in 1921. From 1923–1929 he was Privatdozent for Experimental Physics at Göttingen, later becoming Professor. As Rockefeller Fellow he was at the California Institute of Technology from 1927–1929. From 1929–1930 he was guest professor at the Imperial Universities of Japan and Tsin-Hua University, China. He has been Associate Professor of Physics at California Institute of Technology since 1929 and since 1932 in charge of the Cryogenic Laboratory there. His field of research is low temperature physics and physics of the solid state (crystals, glasses, colloids).

Mrs. S. Scott Goetz, wife of Dr. Alexander Goetz, was born in Philadelphia. She was graduated from Bryn Mawr College.

Picture and biography of Dr. Carl Kenty appeared in the January, 1938, issue of the *Journal of Applied Physics* on p. 36.

Andrew Gemant received his M.D. from the University of Budapest in 1919, and his Ph.D. from the University of Berlin in 1922. After several years in the Research Laboratories of the Siemens Company, Berlin, he became Associate Professor at the Polytechnic University, Berlin. From 1934 he was at the Oxford University, England, and is now Research Fellow in the Engineering Department of the University of Wisconsin.

Raymond D. Mindlin received his B.A. degree from Columbia University in 1928, his B.S. degree in engineering in 1931, his C.E. degree in 1932, and his Ph.D. degree in 1936. He was Research Assistant in the Department of Civil Engineering at Columbia University from 1932 to 1936, and has been Instructor in Civil Engineering at Columbia since 1937.

P. D. Mindlin

W. H. Wells

F. N. D. Kurie

A. Gemant

A. Goetz

Contributed Original Research

On the Starting of Hg Vapor Discharge Tubes

CARL KENTY
General Electric Vapor Lamp Company, Hoboken, N. J.
(Received May 21, 1938)

In a commercial method of starting the Cooper Hewitt Hg vapor lamp, a current of about 0.7 amp. is first made to flow in a circuit containing an inductance and a Hg vacuum switch or "shifter." This shifter is then opened magnetically and the resulting arc therein is unstable and begins to go out. But the inductance acts to keep the current flowing and develops a high voltage which is impressed as a negative kick of about 1000 volts, in the average case of starting, on the Hg pool cathode of the main tube. This kick, as a result of the action of a strip of tinfoil on the outside of the cathode bulb surrounding the Hg pool edge and connected to the main anode, starts the arc. The whole process results in the transfer of nearly the entire current from the shifter arc to the main arc in a time of the order of a few microseconds. The initiation of the cathode spot is attributed to the action of a high electric field at the Hg pool edge existing between this edge and the tinfoil on the outside of the glass. In accord with this theory is the fact that anything which can be done to cause the Hg to wet the glass at the pool edge at a number of points (thereby increasing the field) such as by baking a little carborundum powder on the glass at the edge, helps starting enormously.

If the anode of the tube is disconnected, simple electroscopes show that the walls of the tube everywhere become charged to a negative potential of the order of 10,000 volts as a result of the kicks. High speed electrons are thus evidently shot up the tube. Ionization produced by these probably forms the beginning of the positive column. After initiation, the current in the tube rises to a maximum at a rate limited by the inductance in the circuit and then decreases to a low value sometimes going out altogether. This decrease is shown to be due to an extreme deficiency of Hg vapor in the tube caused by the electrical clean-up of Hg on the walls. Violent voltage surges set in across the tube at this time and a hissing noise is heard. The region of aggravated low pressure can be seen as glowing weak and reddish compared to the blue white of the rest of the tube. This appearance vanishes when, as a result of the rising vapor pressure due to heating, the hiss and surges stop. The surge period may endure many seconds in cold weather before the arc is able to pick up.

THE method which has been used for many years for initiating the arc in the commercial Cooper Hewitt lamp (Fig. 1) has been described by Buttolph and Dana[1] who discuss the historical background of the method and many of the observed phenomena and report recent experiments leading to important improvements in the electrical circuits for applying the method. Referring to Fig. 1, which represents the d.c. case, the method may be described briefly as follows: When the circuit is closed a current of about 0.7 amp. flows through the inductance L, vacuum switch[2] or "shifter" S and resistances

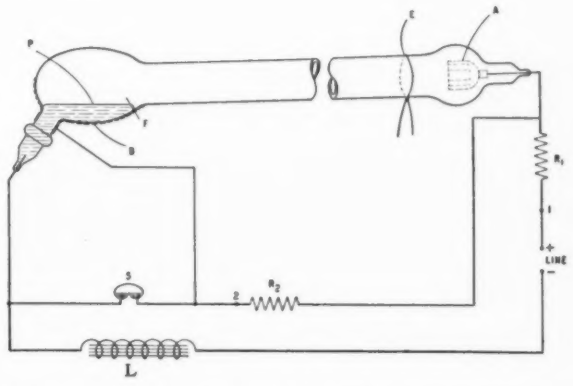

FIG. 1. Diagram of type of d.c. Cooper Hewitt lamp used and connections. Length of tube: 50 inches; diameter of tube: 1 inch; P: mercury pool cathode; A: anode; B: tinfoil "starting band"; L: ¼ henry inductance; S: Hg vacuum switch or "shifter" operated by L; R_1: ballast resistance; R_2: shifter resistance.

[1] L. J. Buttolph and D. W. Dana, Rev. Sci. Inst. **4**, 206 (1933). See also R. C. Kelting and L. J. Buttolph, Trans. I. E. S. **33**, 643 (1938).

[2] In the present experiments a Hg vacuum switch was used. More recently a metallic vacuum switch has been

R_1 and R_2. The magnetism of L then opens S with the result that a negative voltage kick of the order of 1000 volts or more is applied to the Hg pool cathode P. This kick with the help of the action of the so-called starting band B, a tinfoil strip cemented on the outside of the cathode bulb surrounding the Hg pool edge, initiates the arc in the tube.

In the oscillogram[3] of Fig. 2, I_L is the current in the inductance, I_s the current in the shifter

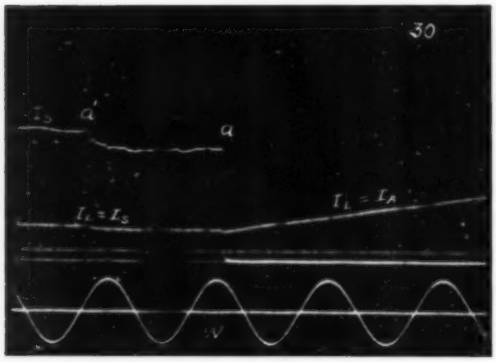

FIG. 2. Oscillogram of the starting of a Cooper Hewitt lamp. I_s: current in shifter as measured by an oscillograph vibrator connected across a small resistance at 2, Fig. 1. I_L: current in inductance measured by a vibrator across a small resistance at 1, Fig. 1. W: 60-cycle timing wave. Arc in main tube starts at a when shifter arc goes out. Note that to the left of a, $I_L = I_s$ and to the right of a, $I_L = I_A$, the arc current in the tube.

and I_A the current in the tube. At a^1 the mechanical separation of the Hg pools in S occurs with the production of an arc. This arc persists somewhat unsteadily till at the point a it becomes unstable. What then happens may best be described with reference to the schematic Fig. 3. Here the instability of the shifter arc just mentioned occurs at a_1 and I_L starts to decrease with the production of high voltage. This initiates I_A and then I_s and I_A decrease and increase respectively in such a way that always $I_s + I_A = I_L$. The voltage developed by L will be

$$V_L = -L(\Delta I_L/\Delta t)$$

and this will appear across S and across the main tube as well as between P and B and between P and A. With $V_L = 1000$ volts, measured as described below, $L = \frac{1}{4}$ henry and $\Delta I_L = 2$ percent of $I_L = 0.014$ amp. (in Fig. 2, ΔI_L at a is 5 percent of I_L but inspection of a large number of oscillograms shows that this is an abnormally large value), this equation gives $t = 4 \times 10^{-6}$ sec. Thus it appears that in a few microseconds the current is transferred from the shifter arc to the main arc with only a slight diminution.

The order of magnitude of V_L was obtained with the help of a sphere gap connected across the tube (from A to P Fig. 1) with a 1000 ohm electrolytic protecting resistance. Tests with 11 different tubes and 1500 shifter operations showed that if the gap setting[4] were under 600 volts a spark always took place across the gap and the tube did not start. As the gap setting was increased beyond this value some starts began to be registered by the easier starting tubes. At 1000 volts a few starts were registered by the harder starting tubes. Finally at 3000 volts no more gap breakdowns were observed and on the average the arc started in about 85 percent of the shifter operations. At 1000 volts, on the average, starts and gap breakdowns occurred with about equal frequency. If the tube were slowly rolled at the time of the shifter kick,

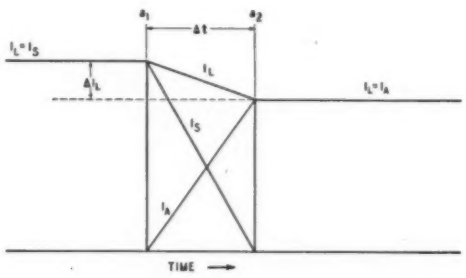

FIG. 3. Schematic view of the starting of a Cooper Hewitt lamp. To the left of a_1 all the current is in the shifter arc; to the right of a_2 it is all in the main arc; in between it is divided schematically as shown.

developed by Mr. W. R. Walker of this laboratory (U. S. Pat. 2076755) which gives a relatively very sharp electrical break between W contacts in a high vacuum and which operates many times per second. This device has improved the starting of the Cooper Hewitt lamp to the point where it is practically instantaneous.

[3] The oscillograms of Figs. 2, 8, 9, 10 were taken by Mr. W. R. Walker and his assistants.

[4] After each spark the sphere gap was cleaned by drawing a paper with some friction between the spheres ($\frac{3}{8}$-inch steel ball bearings) and reset. Breakdown voltages for the gap were taken from Schuman's *Electrische Durchbruchfeldstärke von Gasen* (Springer, 1923). In one-third of the tests the gap was irradiated by a strong Ra preparation but no increase in the likelihood of spark-over was noted. From this it was inferred that the voltage pulses were probably of longer duration than 10^{-7} sec. (See J. Slepian, *The Conduction of Electricity in Gases*, p. 102.)

the average starting voltage was somewhat lower. Such rolling tended to sharpen the receding Hg edge.

While all curves are shown straight in Fig. 3, for simplicity, it is of course not necessary that they be so. In case I_L is curved Δt will be longer than calculated. Also I_A may start at any time between a_1 and a_2, this time probably varying in different cases. Further if Δt is very short it will be necessary to consider the currents which charge and discharge the Hg tinfoil condenser (between P and B, Fig. 1, denoted below by C). Taking the area of the pool as 20 cm², the thickness of the glass as 1 mm and the dielectric capacity of the glass as 7, calculation gives $C=1.2\times10^{-10}$ farad. To charge this condenser to 1000 volts in say 2×10^{-6} sec. would require an average current of 0.06 amp. Such currents would not modify Fig. 3 appreciably; but if Δt were much shorter than 4×10^{-6} sec., as imperceptible values of ΔI_L on many oscillograms indicate it may be in some cases, these currents could become very important.

In Fig. 4 an attempt is made to show schematically one out of probably many possible

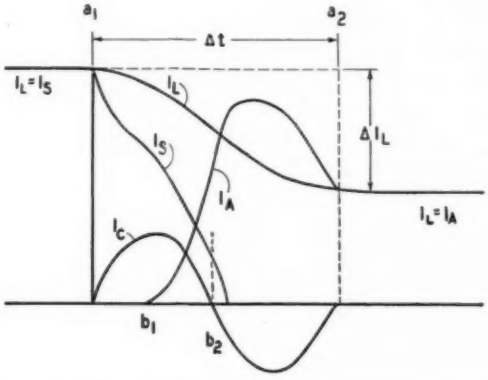

FIG. 4. Schematic relationships of currents during the starting of a Cooper Hewitt lamp. I_e is current to Hg tinfoil condenser (Fig. 1). I_c and (correspondingly) I_L are chosen for simplicity as sections of sine curves.

refinements of Fig. 3, including this condenser current (I_c). Here ΔI_L is shown greatly exaggerated for clarity. While I_L is decreasing at an increasing rate (curvature of I_L positive), as between a_1 and b_2, Fig. 4, C is charging; and when the curvature of I_L is negative, as beyond b_2, C is discharging into the main tube. Thus for a while $I_A > I_L$. At some point b_1 (which may be

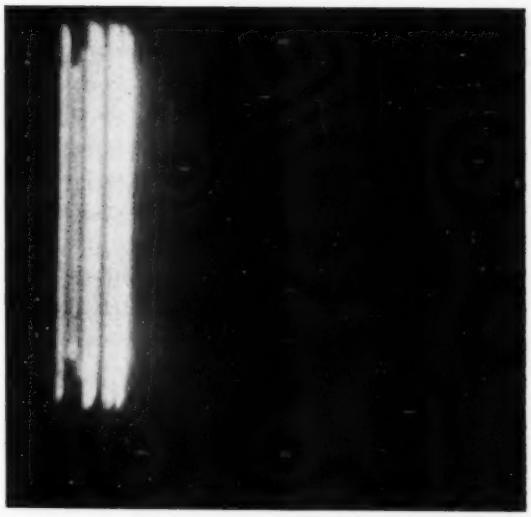

FIG. 5. Cathode-ray oscillogram of potential across shifter during current interruption. Anode of main tube disconnected.

quite variable), the main tube current I_A may be supposed to start and to increase along some such curve as shown. The curves are drawn so that (a) $I_s+I_c+I_A=I_L$ at all times, (b) $I_c=0$ when $d^2I_L/dt^2=0$ and (c) that the areas under I_c above and below the line are equal.

In case high frequency oscillations are present these will be superposed on the general scheme of Fig. 3 or 4. Some evidence for the existence of a sustained oscillation of frequency seemingly greater than 10^7 sec.$^{-1}$, during the period of the shifter arc, and probably before as well as possibly after the electrical break, was obtained when a suitable detecting circuit was loosely coupled to the shifter circuit. The origin of such oscillations is not clear; for oscillations involving all of L and C would be much too slow, having a period $2\pi(LC)^{\frac{1}{2}}=2\pi((\frac{1}{4})\times1.2\times10^{-10})^{\frac{1}{2}}=36\times10^{-6}$ sec. However, higher frequency oscillations might be possible which largely avoided the inductance by making use of its distributed capacity.

The effect of C in suddenly taking a current (I_e) as in Fig. 4 represents the well-known action of a condenser in rendering an arc unstable.

If a second tube were connected directly in parallel with the tube of Fig. 1 and the starting bands removed from both and a single movable starting band provided (a dish of acidulated

water), it was found that, an arc of 1 amp. or less having been started in one lamp, this arc could often be transferred to the other lamp simply by transferring the starting band to the other lamp. Thus one lamp will act as shifter to the other. On the average an arc in a lamp or shifter with a starting band could be operated at a slightly lower current than if no starting band were present. Here the starting band confers the ability to regenerate a cathode spot but also contributes to the instability of the arc by condenser action as above-mentioned so that it is the net effect of the two actions which is observed.

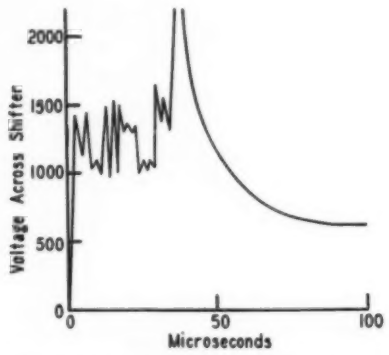

FIG. 6. Cathode-ray oscillogram of potential across shifter during current interruption: Fig. 5 transcribed to rectangular coordinates.

It was found not necessary for starting that the starting band be connected as shown in Fig. 1; even if floating it seemed to be of some slight help, and if its capacity were increased by hanging a 15 cm square plate from it or a 6 ft. wire, almost normal starting could be obtained in many cases.

THE INITIATION OF THE CATHODE SPOT AND POSITIVE COLUMN

The electric field, at the edge of P, Fig. 1, where the Hg is shown meeting the glass at its normal angle of contact, e.g., at F, will, at the time of a voltage kick as above considered, be of the order of $V_L\ K/d$ that is $1000\times7/0.1 = 7\times10^4$ volts/cm. In case the Hg wets the glass so that sharp points or edges are presented, this field could easily be amplified to the value which Beams[5] has shown will produce sufficient field emission to start a discharge, namely, 3.5×10^5 V/cm to 1.8×10^6 V/cm, the highest value being for the purest surface. Now it was early found experimentally that starting could be vastly improved by any means which would make the Hg wet the glass at a number of points (cf. the above-mentioned effect of rolling the tube). One of the most satisfactory means of doing this was found to be the burning of a layer of carborundum crystals into the glass in the region of the Hg edge. This method has been used commercially up to the present time. It seems also possible that points may be further pulled out and sharpened by the electrostatic force in the times involved according to the theory of Tonks.[6] In this connection, if the inside of the cathode bulb is watched in darkness at the time of the shifter kick (the anode having been disconnected) many minute stars of light can be seen, some on the Hg surface, but mostly at the edge where the Hg meets the glass.[7] From these points at the Hg edge small bursts of ionization (luminosity) in the bulb sometimes take place and from them very often luminous streamers and tree shaped figures, faintly suggestive of Lichtenberg figures, spread out over the inner surface of the glass (the whole bulb was coated with a black conducting paint, as is the commercial practice, to prevent the distracting effect of the wandering cathode spot. A large charge could therefore be held on the inner surface of the bulb by condenser action,[8] the paint being of course in contact with the tinfoil band and therefore with the anode). The mechanism of these streamers is not clear; but it may be supposed that through their action large quantities of electrons are drawn out from the points and distributed over the glass. High current density at the above-mentioned points or filaments could, by local heating of the Hg help to give that considerable vapor pressure which Compton has shown to exist in front of the

[5] J. W. Beams, Phys. Rev. **44**, 803 (1933).

[6] L. Tonks, Phys. Rev. **48**, 562 (1935).

[7] If a $2\mu f$ condenser were connected between the anode and the line so that an appreciable charge could flow, one of these luminous points at the Hg edge could be seen to develop into a bright and undoubtedly true cathode spot.

[8] This charge could sometimes be observed to "flash back" if the anode were disconnected and if after the kick had taken place the tube were rolled slightly.

cathode spot.[9] Also Hg will be evaporated, probably at an increasing rate as high speed ions impinge on the cathode spot. It may be supposed that ions will be formed and collect increasingly in front of the spot in such a way that as the total applied voltage decreases the field in front of the spot nevertheless remains at all times that required by Langmuir's field emission theory of the cathode spot.[10]

No attempt will be made to trace all the details of the formation of the positive column, but a few of the probable processes may be mentioned: the projection of high speed electrons up the tube in the early stages as from an electron gun and the formation of ions by these, the charging up of the whole inner surface of the cathode bulb to the pool potential, the appearance of wall charges on the tube with the formation of a high gradient therein (not necessarily uniform), the gradual lowering of this gradient to the normal uniform positive column value as the degree of ionization builds up.

Experiments with anode Disconnected

If the anode in Fig. 1 were disconnected the whole tube including the anode could be charged to a high negative potential by the shifter kick. A small electrostatic voltmeter connected to the anode thus registered as high as $-10{,}000$ volts after some kicks. Small electroscopes hung from the tube at various points indicated similar potentials along the whole tube. These electroscopes were simply pairs of No. 36 Cu wires about 4 cm long hung to swing freely from a small ring which in turn was supported by a wire wrapped around the tube (see *E*, Fig. 1). After rough calibration these simple instruments were of great use in permitting the potential changes in the tube to be followed visually.

A tinfoil band wrapped around the tube at its center and charged to $-10{,}000$ volts by a Wimshurst machine was able to screen the anode from all effects of the shifter kick, and to prevent starting with normal anode connection; at $+10{,}000$ volts, however, this band allowed normal charging effects and starting and indeed seemed to assist somewhat the latter.

It was also observed that with normal anode connection, a kick would sometimes, especially in cold weather, fail to start the tube but would leave the walls with a high negative charge. Such a charge would obviously, in the light of the above, hinder starting on following kicks. Buttolph and Dana[1] mention this phenomenon and describe how the charge can be removed by stroking the tube with the hand or a moist cloth whereupon normal starting can be obtained. It was also observed that a shifter kick would, by some mechanism which is not clear, itself sometimes permit the charge, especially in regions near the cathode end, to flash back and leave the tube uncharged.

If a pool of Hg were allowed to run along the tube from end to end the walls could be thus charged negatively to several thousand volts as the electroscopes showed.

No positive charges were observed in the tube except when the direction of the current in the inductance was changed so that the pool received a positive kick. In this case the positive charges were relatively feeble and reached only a short way up the tube.[11] They were accompanied by flashes of light visible in darkness which were, however, much fainter than the flashes accompanying the negative kicks.

Straight tracks through Hg droplets condensed on the tube walls were early noticed and

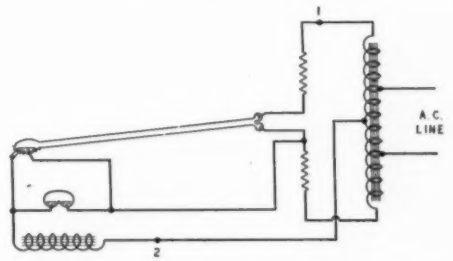

Fig. 7. Circuit for operation of lamp as a rectifier on a.c.

[9] K. T. Compton, Phys. Rev. **37**, 1077 (1931). Compton estimated this pressure to be between 0.75 and 19.6 mm of Hg which is of the order of thousands of times the pressure existing in the remainder of the cathode bulb at starting in the present case.

[10] I. Langmuir, Science **58**, 290 (1923); G. E. Rev. **26**, 735 (1923); Compton reference 9 and papers therein mentioned. R. C. Mason, Phys. Rev. **38**, 427 (1931).

[11] Observation in darkness in this case reveals small sparks taking place between the Hg pool and Hg droplets close by on the glass. In virtue of the capacity between such drops and the tin foil, opposite, such drops could act momentarily as cathodes. A flash of ionization (or momentary plasma) in the bulb, in potential intermediate between the tin foil and the Hg pool, could then charge up nearby regions to its potential, i.e., positively to ground.

found to be due to particles of carborundum shot up the tube at the time of the shifter kick by the large electrostatic forces.[12] Carborundum crystals can sometimes be noticed in practice in the case of hard starting tubes lying all along the bottom of the tube.

Figure 5 is the trace made by a Dufour cathode-ray oscillograph when one pair of plates was connected to an oscillator of 20,000 cycles per sec. frequency and the other pair was connected directly across the shifter (Fig. 1). The total exposure was 0.05 sec. and a suitable mechanism caused the shifter kick to take place in this interval. The anode was disconnected. Fig. 6 shows the deflection transcribed to rectangular coordinates.[13] A rather discontinuous

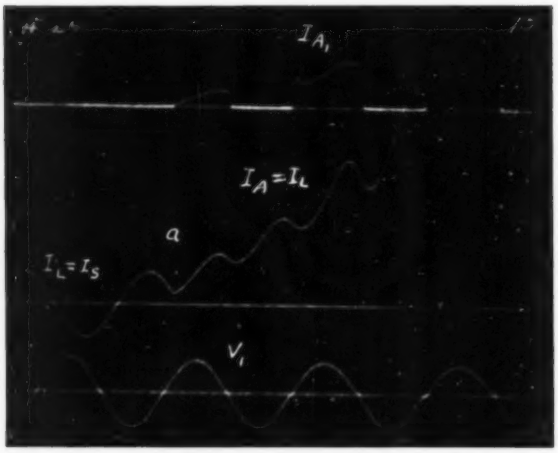

FIG. 8. Oscillogram of normal starting of lamp in circuit of Fig. 7. Starting takes place at a at which time I_L transfers from shifter arc to main arc in tube.

average potential of about 1000 volts is seen to exist across the shifter (and therefore also essentially across the inductance and Hg tinfoil condenser, Fig. 1) for about 40 microseconds.[14] The potential then rises abruptly to an unknown value and then decreases continuously toward zero. Now a decrease of I_L of 0.16 amp. over a period of 40×10^{-6} sec. would give the observed 1000 volts ($L=\frac{1}{4}$ henry). This leaves $0.7-0.16=0.54$ amp. still flowing in the inductance at the time of the final break. If all the energy of L were to discharge into the Hg tinfoil condenser at this time its potential would be raised to a maximum value V_m given by $\frac{1}{2}CV_m^2=\frac{1}{2}LI_L^2$; here C will be taken as 3.6×10^{-10} farad, i.e., 3 times the value above calculated, since, because of the starting process the whole inner surface of the bulb (opposite the black paint) can charge up and not merely that part covered by the Hg pool. Taking $L=\frac{1}{4}$ henry as before it then follows that $V_m=14{,}000$ volts. In view of the fact that the inductance itself has a distributed capacity such a value of V_m is not unreasonable since developed voltages of 10,000 have been observed as above noted. After I_L has become zero, C will discharge back through L. Here only $\frac{1}{3}$ of C as above calculated will participate, at least initially, because the charge on that part of the inner surface of the bulb not covered by Hg will remain on the glass. (Subsequent flash-over of this charge could partly explain why the curvature of the smooth part of the curve to the right in Fig. 6 is wrong for the discharge of a condenser through an inductance. Also sparks or corona discharge across L or elsewhere could contribute to the observed curvature.) An oscillogram will now be shown which can only be explained on the basis of such a charging up of C and discharge back through L.

STARTING IN A.C. OPERATION

In Fig. 7 is shown a simple circuit for the operation of a lamp on a.c. and Fig. 8 is a magnetic oscillogram of normal starting. Here I_L or I_A represents the e.m.f. across a small

[12] Probably also Hg droplets, perhaps adhering loosely to the glass near to the Hg pool edge, are shot up the tube; it further seems possible on Tonks' theory of surface rupture (reference 6) that very fine (negatively charged) Hg droplets could be pulled off points at the Hg edge by the field. Droplets shot up the tube will carry whatever impurity they have with them, either held as an amalgam or otherwise, and when they evaporate leave this behind on the tube walls.

[13] The oscillogram of Fig. 5 (with its transcription in Fig. 6) is one of several made by Mr. John A. Tiedeman in 1929 at the General Engineering laboratory of the General Electric Company, at Schenectady, under the direction of Mr. C. M. Faust. I am indebted to Mr. Faust for permission to use this photograph.

[14] Since here I_L must decrease all the way to zero and not merely by a few percent as in cases of actual starting (where the anode is connected) the time scale of Fig. 6 is perhaps not incompatible with the starting times of a few microseconds arrived at above. Cathode-ray oscillograms of actual starting would be very desirable. The sharp voltage discontinuities in Fig. 6 might correspond to the successive formation of partial cathode spots (possibly the individual bright starts above noted).

resistance inserted at 2, Fig. 7, and $I(A_1)$ that across a small resistance inserted at 1. V_1 is the e.m.f. across the upper half of the auto-transformer. At a the electrical break in the shifter arc took place and the current was transferred to the tube, building up thereafter as shown. Somewhat before a, but presumably in the same current half-cycle, the mechanical break in the shifter took place.

Now in the case of a.c. the mechanical break in S will be as likely to take place with I_L in one direction as in the other, and when I_L is in the wrong direction the tube would not be expected to start. Oscillograms show, however, that occasionally starting does take place when I_L is in the wrong direction. Fig. 9 is an example of

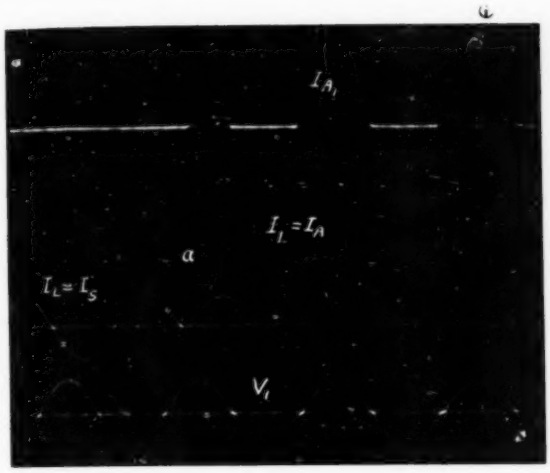

FIG. 9. Oscillogram of unusual starting on a.c. when I_L was in the wrong direction. A sudden reversal of the current in the inductance occurs at a.

this. Here the electrical break occurs at a and there is a sudden reversal of current in L (presumably the mechanical break must have taken place just to the left of a, in the same current half-cycle). Now there seems to be no other way by which I_L could suddenly be reversed than by the charging up of C and discharge back through L as above discussed. (The complete period of this electrical oscillation is about 36×10^{-6} sec. as above calculated.) In the course of this oscillation, after I_L, now flowing in the right direction through L for starting, has passed a maximum, C will be charging up in the proper direction and starting may be supposed to take place normally in the manner of Fig. 3 or Fig. 4 (except that I_s is not now present).

THE SUBSEQUENT COURSE OF THE CURRENT: THE CLEAN-UP OF HG VAPOR AND SURGES

The oscillogram of Fig. 10 for the d.c. case shows the behavior of the current for sometime

FIG. 10. Oscillogram of starting of d.c. Cooper Hewitt lamp. Circuit as in Fig. 1 and notation as in Fig. 2.

after the initial starting process. Measurement shows that the value of LdI/dt in such oscillograms in the region between a and b is of the order of 40–70 volts.[15] Substracting this from 115 volts leaves a reasonable voltage for the arc and resistance drops. (R_1 in Fig. 1, is of the order of a few ohms.) It is therefore concluded that in this region the current is rising as fast as L will allow (see below). The initial value of LdI/dt (immediately beyond a) often seems nearly equal to the line voltage; this suggests that as a result of the shifter kick the tube is left in a state of relatively high conductivity.

After passing a maximum which may be as high as 10 amp. (tube at room temperature) the current is seen to descend again to nearly its initial value of 0.7 amp. After this it begins a slow rise toward an equilibrium value of 3.7 amp. as equilibrium temperature conditions are attained.

The cause of the decrease of current beyond b was found to be a condition of abnormally low Hg vapor pressure due to the clean-up of Hg vapor on the walls of the tube by the arc at a rate too fast to be compensated for by normal evaporation from the free Hg surfaces. A special study of this clean-up phenomenon was made

[15] Although the value of dI/dt is increasing toward the maximum of the current peak in Fig. 10, the product LdI/dt is really decreasing because the effective value of L is decreasing due to saturation of its core. The values of LdI/dt mentioned were based on the effective values of L as measured separately.

FIG. 11. Starting of a d.c. Cooper Hewitt lamp showing voltage surges (V_T) which develop across the lamp due to low pressure caused by clean-up of Hg vapor. The time between *a* and *b* is about 0.02 sec.

which is reported in the following paper. Beyond *b*, a marked hissing noise can be heard to emanate mainly from the inductance. This noise was found to be associated with voltage surges across the lamp caused by very low pressure. Such surges have frequently been observed in the anode arms of Hg rectifiers carrying large currents. Langmuir and Mott-Smith[16] showed that for a given tube diameter and Hg vapor pressure, there is a critical current, varying approximately as the square of the pressure, above which surges occur. While the above hissing noise lasts, a greater or lesser length of the arc, usually situated in the middle or toward the anode end, is seen to be relatively weak in light and to have a reddish or yellowish hue.[17] This was also found to be an excellent indication of low pressure. Thus the region can be seen in which the aggravated condition of low pressure exists. The subject of surges is discussed further in another paper* as well as certain electrophoretic effects which are involved.

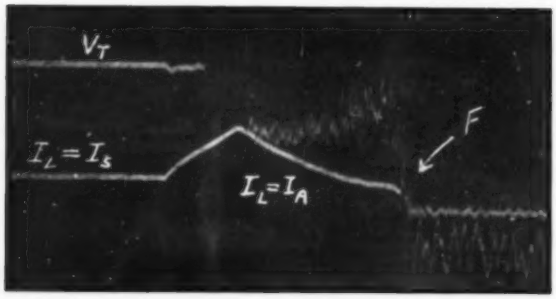

FIG. 12. Extinction (at *F*) of newly formed arc in Cooper Hewitt lamp due to loss of Hg vapor by clean-up. Time scale approximately as in Fig. 11.

[16] I. Langmuir and H. M. Mott-Smith, Jr., G. E. Rev. **27**, 762 (1924).

[17] Colors other than red are believed to be associated with traces of gases other than Hg.

* To be published in this journal.

In order to study the voltage surges across the tube a test coil of a few turns was placed around the inductance and connected to one of the two strings of a string oscillograph. An example of the trace made by this string is shown at V_T, Fig. 11. Here I_L as measured by the other string is the current through L as before (zero position of I_L string not shown in Figs. 11–14. The use of a relay to complete the V_T circuit only after the tube had started avoided the shifter kick and allowed the string to be used at a greater sensitivity. V_T shows that with the attainment of the current maximum (in this case about 5 amp.) surges set in across L (and therefore across the tube) which soon gain large proportions. These surges may continue for a second or more be-

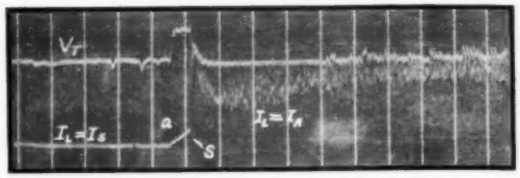

FIG. 13. The effect of short circuiting the inductance (at *S*). Time between vertical lines: 0.01 sec.

fore the pressure deficiency is finally overcome. Fig. 12 shows a case where the arc went out (at *F*) with the development of such a large surge that the V_T string was permanently stretched.[18] Such cases are quite frequent especially in cold weather.

When the temperature is only a few degrees *C* such flashes may be repeated many times before an arc is finally able to continue. Each flash will of course heat the tube somewhat and thereby raise the Hg vapor pressure. The condition of low pressure is most aggravated in these cases and the "hiss" period may last for 10 seconds or more. Sparks have been observed in such cases indicating surge voltages of many thousand volts.

The height of the current maximum, other things being equal, is dependent on the vapor pressure in the tube and the condition of the walls as regards saturation with Hg (see paper

[18] Since the cathode spot is unstable at these low currents (of the order of an ampere or less) it is impossible to say in such cases whether the arc went out on account of difficulties in the positive column or at the cathode spot.

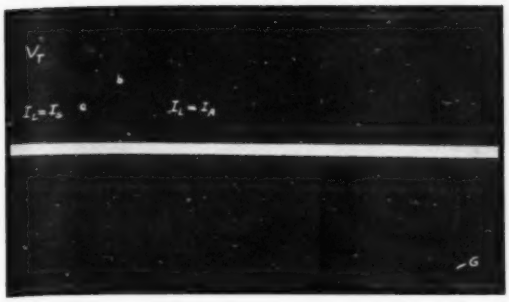

FIG. 14. Breakdown of gap (at G) connected across tube during surge period.

to be published). Thus at 20°C it may reach 10 amperes as above noted but at 2°C it rarely exceeds 1 ampere and in this case the surges set in almost immediately.

In Fig. 13 a relay was used to short circuit the inductance at S. The arc current is seen to rise abruptly to a high value and then decrease and pass through a flat minimum. It is seen to be extremely fluctuating. Such oscillograms show clearly that the initial rate of current rise is limited by the inductance as above noted. In many cases such a short circuiting of L put out the arc either immediately or soon afterward, but in a surprisingly large number of cases, like Fig. 13, it did not. Perhaps the explanation is that without L the current is able to adjust itself quickly at all times to whatever pressure conditions develop in the tube, whereas with L present a condition of low pressure developing is aggravated by the tendency of L to keep the current constant. Evidence is given in the later paper that for a given average current, more Hg is lodged on the walls if surges are present than if they are not.

Figure 14 shows a case where a spark gap set to break down at 1370 volts was connected across the tube (in series with a 1000-ohm electrolytic resistance to protect it). Here the sensitivity of the V_T string was reduced to allow it to withstand the shifter kick. After a surge period which lasted nearly 0.3 second a surge occurred (at G) which was observed to break down the gap, and the arc was put out. Many such cases were observed where the surge voltage was higher than that of the shifter kick which started the arc.[18]

These experiments were carried out in 1928–29, at Princeton. I wish to express my thanks to Dr. R. D. Mailey and Dr. L. J. Buttolph of this company who suggested the present study and who supplied a wealth of facts and suggestions during the course of its prosecution; to the General Electric Vapor Lamp Company, for financial aid; to Dr. K. T. Compton for extending the facilities of the Palmer Physical Laboratory and for helpful suggestions; and to Dr. R. C. Mason with whom I had the opportunity of discussing many of these problems.

Stresses in a Heavy Disk Suspended from an Eccentric Peg

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An exact solution of the two-dimensional elasticity equations for small strain is obtained which satisfies the boundary conditions for a heavy disk suspended in a vertical plane from an eccentric peg of small diameter.

INTRODUCTION

A SOLUTION will be given for the stresses in a circular disk supported with its plane vertical by a peg located at any point, A, on a vertical diameter (Fig. 1). The diameter of the eccentric peg is assumed to be small in comparison with the diameter of the disk so that the peg may be replaced by a concentrated force F. The thickness of the disk is assumed to be small in comparison with its diameter and functions in the stresses involving the coordinate normal to the plane of the disk are neglected. The problem is therefore strictly two-dimensional.

On account of the eccentricity of the balancing force, the problem is most conveniently handled in bipolar coordinates. Such a coordinate system may be obtained from the conformal transformation

$$x+iy=ia\coth\tfrac{1}{2}(\alpha+i\beta), \tag{1}$$

whence

$$x=\frac{a\sin\beta}{\cosh\alpha-\cos\beta},\quad y=\frac{a\sinh\alpha}{\cosh\alpha-\cos\beta} \tag{2}$$

$$\alpha=\log(r_1/r_2),\qquad \beta=\theta_1-\theta_2. \tag{3}$$

The significance of these coordinates is illustrated in Fig. 1.

Important parts are taken in the solution by the stretch ratio, J, of the transformation and the angle ϕ which the tangent to the curve $\beta=$constant makes with the x-axis. These are given by

$$J=\left[\left(\frac{\partial x}{\partial\alpha}\right)^2+\left(\frac{\partial y}{\partial\alpha}\right)^2\right]^{\frac{1}{2}}=\frac{a}{\cosh\alpha-\cos\beta}, \tag{4}$$

$$\phi=\theta_1+\theta_2+\frac{\pi}{2}=\tan^{-1}\frac{\cosh\alpha\cos\beta-1}{\sinh\alpha\sin\beta} \tag{5}$$

The components of stress in plane bipolar coordinates are expressed in terms of a stress function χ and a body force potential Ω by[1]

$$\left.\begin{aligned}
a\widehat{\alpha\alpha}&=\left\{(\cosh\alpha-\cos\beta)\frac{\partial^2}{\partial\beta^2}-\sinh\alpha\frac{\partial}{\partial\alpha}\right.\\
&\qquad\left.-\sin\beta\frac{\partial}{\partial\beta}+\cosh\alpha\right\}\left(\frac{\chi}{J}\right)+a\Omega\\
a\widehat{\beta\beta}&=\left\{(\cosh\alpha-\cos\beta)\frac{\partial^2}{\partial\alpha^2}-\sinh\alpha\frac{\partial}{\partial\alpha}\right.\\
&\qquad\left.-\sin\beta\frac{\partial}{\partial\beta}+\cos\beta\right\}\left(\frac{\chi}{J}\right)+a\Omega\\
a\widehat{\alpha\beta}&=-(\cosh\alpha-\cos\beta)\frac{\partial^2(\chi/J)}{\partial\alpha\partial\beta}
\end{aligned}\right\}, \tag{6}$$

where Ω is related to the x and y components of the body force per unit of volume by

$$X=-\partial\Omega/\partial x,\quad Y=-\partial\Omega/\partial y \tag{7}$$

and χ satisfies the differential equation

$$\nabla^4\chi=-(1-\nu)\nabla^2\Omega, \tag{8}$$

in which ν is Poisson's ratio, ∇^2 is Laplace's operator, and $\nabla^4=\nabla^2\nabla^2$.

Since the disk is situated in a uniform gravitational field directed along the Y-axis, the body force system is given by $X=0$, $Y=w$ where w is the weight per unit of volume of the disk. Hence $\Omega=-wy=-wJ\sinh\alpha$ and $\nabla^2\Omega=0$, so that (8) reduces to

$$\nabla^4\chi=0. \tag{9}$$

[1] G. B. Jeffery, Phil. Trans. Roy. Soc. **A221**, 265–293 (1920).

A general solution of (9) in bipolar coordinates has been given by Jeffery:[1]

$$\frac{\chi}{J}=(E\cos\beta+F\sin\beta+G\cosh\alpha+H\sinh\alpha)\beta$$
$$+(A_0\cosh\alpha+B_0\alpha\cosh\alpha+C_0\sinh\alpha+D_0\alpha\sinh\alpha)$$
$$+(A_1\cosh 2\alpha+B_1+C_1\sinh 2\alpha+D_1\alpha)\cos\beta$$
$$+(A_1'\cosh 2\alpha+B_1'+C_1'\sinh 2\alpha+D_1'\alpha)\sin\beta$$
$$+\sum_{n=2}^{\infty}\left\{\begin{aligned}&[A_n\cosh(n+1)\alpha+B_n\cosh(n-1)\alpha\\&\quad+C_n\sinh(n+1)\alpha+D_n\sinh(n-1)\alpha]\cos n\beta\\&+[A_n'\cosh(n+1)\alpha+B_n'\cosh(n-1)\alpha\\&\quad+C_n'\sinh(n+1)\alpha+D_n'\sinh(n-1)\alpha]\sin n\beta\end{aligned}\right\}. \quad (10)$$

Boundary Conditions

The boundary of the disk is taken as the circle $\alpha=\text{constant}=\alpha_1$. The edge of the disk is free of stress, so that

$$\text{when } \alpha=\alpha_1: \left\{\begin{matrix}\widehat{\alpha\beta}=0\\ \widehat{\alpha\alpha}=0\end{matrix}\right\}. \quad (11)$$

From the first of (11) and the third of (6) we have

$$(\partial/\partial\alpha)(\chi/J)=\xi \text{ (a constant)}. \quad (12)$$

From (12), the second of (11) and the first of (6) we have

$$\left\{(\cosh\alpha_1-\cos\beta)\frac{\partial^2}{\partial\beta^2}-\sin\beta\frac{\partial}{\partial\beta}+\cosh\alpha_1\right\}\left(\frac{\chi}{J}\right)$$
$$=waJ_1\sinh\alpha_1+\xi\sinh\alpha_1,$$

the solution of which is

$$\chi/J_1=\xi\tanh\alpha_1+\eta(\cosh\alpha_1\cos\beta-1)+\zeta\sin\beta+wa^2\operatorname{cosech}\alpha_1-\tfrac{1}{2}wa^2\operatorname{cosech}^2\alpha_1\phi_1\sin\beta, \quad (13)$$

where η and ζ are constants.

(13) may be written in the form

$$\chi=\zeta J_1\sin\beta+(\xi\operatorname{sech}\alpha_1+\eta\sinh\alpha_1)J_1\sinh\alpha_1-a\eta\cosh\alpha_1+wa^2J_1\operatorname{cosech}\alpha_1-\tfrac{1}{2}wa^2\operatorname{cosech}^2\alpha_1\phi_1J_1\sin\beta$$
$$=\zeta x_1+(\xi\operatorname{sech}\alpha_1+\eta\sinh\alpha_1)y_1-a\eta\cosh\alpha_1+wa^2J_1\operatorname{cosech}\alpha_1-\tfrac{1}{2}wa^2\operatorname{cosech}^2\alpha_1\phi_1J_1\sin\beta, \quad (14)$$

where x_1 and y_1 are the coordinates of a point on α_1. By adding a function linear in x and y to χ, the terms in (14) involving ξ, η, ζ may be removed for one boundary without affecting the stresses. Hence, there being only one boundary in this problem, ξ, η, and ζ may be taken equal to zero and the boundary conditions reduce to

$$\left.\begin{aligned}&(\partial/\partial\alpha)(\chi/J)=0\\&\chi/J=wa\operatorname{cosech}\alpha_1-\tfrac{1}{2}wa^2\operatorname{cosech}^2\alpha_1\phi_1\sin\beta\end{aligned}\right\}. \quad (15)$$

Construction of the Stress Function

The last term in the second of (15) warrants special consideration, for it is observed that no

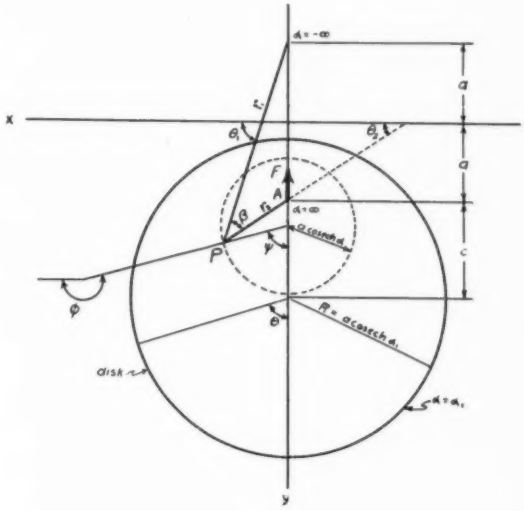

Fig. 1.

similar term appears in (10). It may be verified that the function

$$\chi_1=-\tfrac{1}{2}wa^2\operatorname{cosech}^2\alpha_1J\phi\sin\beta \quad (16)$$

satisfies (9), although it does not appear ex-

plicitly in (10). Observing that a cosech α_1 is the radius, R, of the disk; $\phi=\theta_1+\theta_2+\pi/2$; $J\sin\beta=x$; (16) may be written as

$$\chi_1=-\tfrac{1}{2}wR^2x(\theta_1+\theta_2+\pi/2). \qquad (17)$$

In (17) we recognize the stress function for a pair of single forces acting at the poles $(0, +a)$, $(0, -a)$ in the direction of the negative y-axis. The magnitudes of the forces are equal to $w\pi R^2$ which is the weight of the disk with the thickness taken as unity. Hence (16) is the stress function required to annul the *resultant* of the stresses produced on $\alpha=\alpha_1$ by the gravitational force. We shall therefore introduce it as part of the stress function for this problem.

It is known[2] that the stress function $x\theta_2$ produces many valued functions in the displacements for the region included in the disk. These may be removed by adding the stress function

$$\chi_2/J=\tfrac{1}{4}(1-\nu)wa^2\,\text{cosech}^2\,\alpha_1 \times[\alpha\sinh\alpha-\alpha(\cosh\alpha-\cos\beta)], \qquad (18)$$

which is perhaps more readily recognized when it is written in our other notation:

$$\chi_2=\tfrac{1}{4}(1-\nu)wR^2 \times[(y-a)\log r_2-(y-a)\log r_1]. \qquad (19)$$

The term $(y-a)\log r_2$ in (19) serves to eliminate the many valued displacements in the disk which were introduced by the term $x\theta_2$ in (17).

Hence the awkward term $\phi\sin\beta$ of (15) may be properly eliminated by introducing as part of our stress function χ_1 and χ_2.

Although χ_1 and χ_2 serve to simplify the second boundary condition, they introduce a difficulty of another kind in the first boundary condition. If (16) is substituted in the first of (15), there results

$$\frac{\partial}{\partial\alpha}\left(\frac{\chi_1}{J}\right)=-\tfrac{1}{2}wa^2\,\text{cosech}^2\,\alpha_1\frac{\sin^2\beta}{\cosh\alpha-\cos\beta}. \qquad (20)$$

Again, no term of this type appears explicitly in (10). It is true that (20) can be expanded into an infinite series of cosines. The same is true of $\phi\sin\beta$. But we shall again adopt the technique of introducing suitable finite functions to eliminate awkward terms.

[2] Timoshenko, *Theory of Elasticity* (New York, 1934), p. 116.

The function

$$\chi_3=Aa^{-2}y(x^2+y^2)+Ba^{-1}y^2 =AJ\sinh\alpha\frac{\cosh\alpha+\cos\beta}{\cosh\alpha-\cos\beta}+BJ\frac{\sinh^2\alpha}{\cosh\alpha-\cos\beta},$$

where A and B are constants, is a suitable biharmonic function, i.e., it satisfies (9). It may be verified that, if $A=\tfrac{1}{4}wa^2$ and $B=-\tfrac{1}{2}wa^2\coth\alpha_1$, the awkward term in (20) is eliminated on $\alpha=\alpha_1$ and there remain in the boundary conditions only terms of the form $C+D\cos\beta$.

We are now in a position to select suitable terms of this last type from Jeffery's general solution (10). These are

$$\chi_4/J=A_0\cosh\alpha +(A_1\cosh 2\alpha+C_1\sinh 2\alpha)\cos\beta. \qquad (21)$$

It is readily verified that the proper values for A_0, A_1 and C_1 are

$$A_0=\tfrac{1}{4}wa^2[2\coth\alpha_1-(1-\nu)(\coth\alpha_1-1) +(1+\nu)\,\text{cosech}^2\,\alpha_1]$$

$$A_1=-C_1=-\tfrac{1}{8}(1+\nu)wa^2\frac{\text{cosech}^4\,\alpha_1}{(\coth\alpha_1-1)^2}.$$

The complete stress function is therefore given by

$$\chi/J=\chi_1/J+\chi_2/J+\chi_3/J+\chi_4/J$$

$$=\tfrac{1}{4}wa^2\,\text{cosech}^2\,\alpha_1\Big\{-2\phi\sin\beta$$

$$+(1-\nu)[\alpha\sinh\alpha-\alpha(\cosh\alpha-\cos\beta)]$$

$$+a^{-1}\sinh^2\alpha_1 J\sinh\alpha(\cosh\alpha+\cos\beta)$$

$$-a^{-1}\sinh 2\alpha_1 J\sinh^2\alpha$$

$$-\tfrac{1}{2}(1+\nu)\frac{\text{cosech}^2\,\alpha_1}{(\coth\alpha_1-1)^2}(\cosh 2\alpha-\sinh 2\alpha)\cos\beta$$

$$+[\sinh 2\alpha_1-(1-\nu)\sinh^2\alpha_1(\coth\alpha_1-1) +\tfrac{1}{2}(1+\nu)]\cosh\alpha\Big\}. \qquad (22)$$

Stresses

The formulas for the bipolar components of stress in the disk are found by substituting (22) in (6). The results are

$$\widehat{\alpha\alpha} = -wJ \sinh \alpha - \tfrac{1}{2}w \operatorname{cosech}^2 \alpha_1[a \sinh \alpha(\cosh \alpha - \cos \beta) - J \sinh^3 \alpha]$$
$$+\tfrac{1}{4}(1-\nu)wa \operatorname{cosech}^2 \alpha_1[\sinh \alpha(\cosh \alpha - \cos \beta) - \sinh^2 \alpha] + \tfrac{1}{2}wJ[\sinh \alpha + (J/a) \sinh 2\alpha \sin^2 \beta]$$
$$-wa^{-1}J^2 \coth \alpha_1 \sinh^2 \alpha \sin^2 \beta - (aw/8)(1+\nu) \operatorname{cosech}^2 \alpha_1 e^{2(\alpha_1-\alpha)}(1+2 \sinh \alpha \cos \beta)$$
$$+\tfrac{1}{2}wa[\coth \alpha_1 - \tfrac{1}{2}(1-\nu)(\coth \alpha_1 - 1) + \tfrac{1}{4}(1+\nu) \operatorname{cosech}^2 \alpha_1], \quad (23)$$

$$\widehat{\beta\beta} = -wJ \sinh \alpha + \tfrac{1}{2}w \operatorname{cosech}^2 \alpha_1 J \sinh \alpha \sin^2 \beta$$
$$+\tfrac{1}{4}(1-\nu)wa \operatorname{cosech}^2 \alpha_1[(\cosh \alpha - \cos \beta)(2 \cosh \alpha - \sinh \alpha) - \sinh^2 \alpha]$$
$$+\tfrac{1}{2}wJ[3 \sinh \alpha - (J/a) \sinh 2\alpha \sin^2 \beta] - wa^{-1}J^2 \coth \alpha_1(\cosh \alpha \cos \beta - 1)^2$$
$$-(wa/8)(1+\nu) \operatorname{cosech}^2 \alpha_1 e^{2(\alpha_1-\alpha)}[4(\cosh \alpha - \cos \beta) + 2 \sinh \alpha \cos \beta + 1]$$
$$+\tfrac{1}{2}wa[\coth \alpha_1 - \tfrac{1}{2}(1-\nu)(\coth \alpha_1 - 1) + \tfrac{1}{4}(1+\nu) \operatorname{cosech}^2 \alpha_1, \quad (24)$$

$$\widehat{\alpha\beta} = \tfrac{1}{2}w \operatorname{cosech}^2 \alpha_1[J \sinh^2 \alpha \sin \beta - a(\cosh \alpha - \cos \beta) \sin \beta] + \tfrac{1}{4}(1-\nu)wa \operatorname{cosech}^2 \alpha_1(\cosh \alpha - \cos \beta) \sin \beta$$
$$+\tfrac{1}{2}wJ[\cosh 2\alpha \sin \beta - a^{-1}J \sinh 2\alpha \sinh \alpha \sin \beta] - \tfrac{1}{2}wJ \coth \alpha_1[\sinh 2\alpha \sin \beta - 2a^{-1}J \sinh^3 \alpha \sin \beta]$$
$$+\tfrac{1}{4}(1+\nu)wa \operatorname{cosech}^2 \alpha_1 e^{2(\alpha_1-\alpha)}(\cosh \alpha - \cos \beta) \sin \beta. \quad (25)$$

It is interesting to calculate the stresses $\widehat{\beta\beta}_1$ in the boundary of the disk. These are obtained by substituting $\alpha = \alpha_1$ in (24) with the result:

$$\widehat{\beta\beta}_1 = \tfrac{1}{2}wa \operatorname{cosech}^2 \alpha_1(\cosh \alpha_1 - \cos \beta)$$
$$\times[(1-\nu)e^{-\alpha_1} - (1+\nu) \cos \beta]. \quad (26)$$

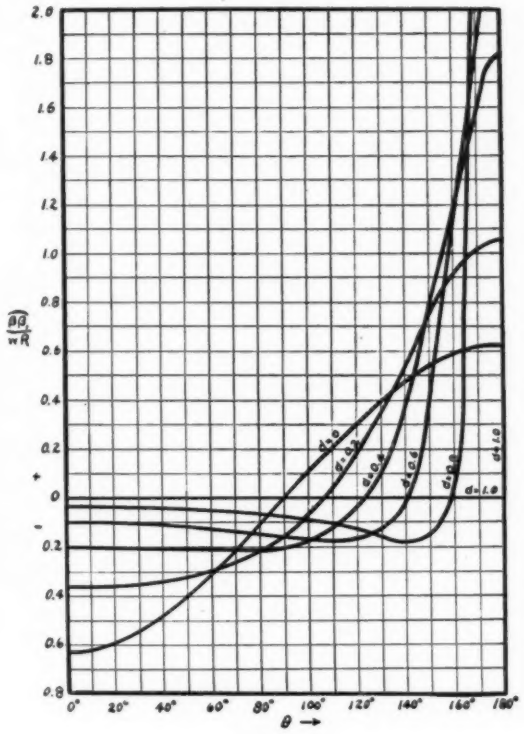

FIG. 2.

This is more easily interpreted in terms of the physical dimensions of the disk. If d is the ratio of the distance of the peg from the center of the disk to the radius R of the disk, then $d = \cosh \alpha$. Also, let θ be the angle which a radius from the center of the disk makes with the y-axis as shown in Fig. 1. Then

$$\widehat{\beta\beta}_1 = \frac{wR(1-d^2)}{2(1+d^2+2d \cos \theta)} \times \left\{(1-\nu)d - (1+\nu)\frac{(1+d^2) \cos \theta + 2d}{1+d^2+2d \cos \theta}\right\}. \quad (27)$$

In Fig. 2, the ratio $\widehat{\beta\beta}_1/wR$ is plotted against θ for various values of $d = c/R$. It is interesting to observe that the stress in the boundary of the disk follows a simple cosine law when the peg is at the center ($d = 0$). When the disk is supported at its outer edge ($d = 1$) the stress in the boundary is zero except at the peg ($\theta = 180°$) where the stress is infinite.

Vitrification and Crystallization of Organic Cells at Low Temperatures

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(Received May 1, 1938)

I. *Theoretical considerations.*—The conditions which determine whether a homogeneous liquid will solidify into the crystalline or into the vitreous state are discussed and a brief account of the rôle of the speed of crystallization, V, and that of grain formation, N, is given. These concepts are applied to the causes of the death due to crystallization of *nondehydrated* organic cells, and the physical conditions of cooling are developed under which such organisms can be solidified with a minimum of crystallization, assuring to this extent the preservation of their potential life.

II. *Technical considerations.*—Methods for obtaining *cooling rates* up to 10^4 deg. sec.$^{-1}$ applicable to organic cells in a highly dispersed state are developed. As subject for the experiments, pure strains of yeast (Saccharomyces cerevisiae) were chosen on account of the high sensitivity to low temperatures. As *death criterion*, the permeability of the cells to a standard aqueous solution of methylene blue was chosen, the death rate was thus determined microphotographically or with a counting chamber. Different techniques of exposure favoring and preventing crystallization are developed.

III. *Experimental results.*—The *rate of cooling* of suspensions of living cells in aqueous media was varied from 1 to 10^4 deg. sec.$^{-1}$ and thus conditions favoring either crystallization or vitrification of the cell plasma were produced. The death rate at an exposure of −185°C was thus varied from approximately 75 percent to approximately 3 percent. The *duration of exposure* at this temperature was varied from 5′ to 6000′; no appreciable influence of the time of exposure was found. The temperature to which the cells were cooled was varied from −50°C to −252°C and it was found that between −185°C and −252°C the temperature did *not* affect the death rate. Above app. −150°C an increase of the death rate was found, and a dependence upon the time of exposure, since the speed of crystallization begins to be appreciable. *Repeated exposures* of the same cells under conditions not especially favoring vitrification were studied and the integral death rate, δ_n (death rate after nth exposure) was investigated with respect to a constancy of the death rate (δ) at each freezing. It appears that the death rate for repeated freezings is not controlled by simple probability relations, but that other effects enter, such as weakening of cells by previous exposures and the selection of cold-resistant cells by survival.

I. THEORETICAL CONSIDERATIONS

a. Crystallization and vitrification

THE transition from the liquid into the solid state by lowering the temperature of the system can occur in two ways: In one case the liquid phase changes into the crystalline; the act of crystallization is then characterized by the emission of the heat of fusion. Thermodynamically speaking, this act reduces the entropy of the system as well as the heat content ($\int_0^T Q dT$) and the free energy is a minimum.* Below the temperature of fusion, the crystalline state is thus the most stable and (in the absence of allotropy) also the most stable down to the lower end of the temperature scale.

Experience has shown, however, that in spite of the high thermodynamic probability of the crystalline state, crystallization does not necessarily take place below the melting temperature. Hence, not all solids are crystalline. This shows that the occurrence of crystallization must depend on certain additional conditions of statistical nature such that the melt is prevented from attaining a higher degree of order (state of larger stability), if these conditions are not fulfilled. In such cases the system remains a "liquid" for the rest of the temperature scale. Needless to say, the word "liquid" refers in this connection to the statistical arrangement of the molecules of the system, in contradistinction to the regularity of the arrangement in a crystal. It does not refer to a number of other physical qualities such as viscosity, etc. In fact, the viscosity soon increases with decreasing temperature to such an extent that the substance is physically solid but not a crystal. This state is generally called the glassy or vitreous state.*

* This is strictly true only for an "ideal" crystal where mosaic structures are absent.

* The following scheme is rather descriptive of the state of a system, representing all possible combinations:

1 Solid	2 Liquid
a Crystal (anisotropic)	*b* Glass (isotropic)

1*a* is a crystalline solid; 2*b* a normal monomolecular liquid; 1*b* a vitreous solid; 2*a* a crystalline liquid (certain organic liquids and probably the second modification of liquid helium). A glass would thus be represented by 1*b*.

It is physically characterized by a continuous increase of the viscosity as the temperature is lowered, by a remaining isotropy and by the absence of any discontinuity at the melting temperature; thermodynamically it is characterized by a higher entropy as well as a higher heat content, the latter resulting from the fact that the heat of fusion remains within the system. (Fig. 1.)

The factors that determine which of the two states will occur when the liquid is brought below its melting temperature are several, and, as they have important bearings on the problem, will be briefly outlined.

Tammann[1] gave the first systematic description of the tendency of a supercooled liquid to form "grains," i.e., nuclear centers of crystallization within itself, and defined the number N of such centers originating at constant temperature per unit time in a unit volume as a characteristic constant for a particular substance. He also showed that N depends upon the temperature in a way as shown qualitatively in Fig. 2a; at T_m (melting temperature) N is zero, but increases rapidly to a maximum value at a temperature in the vicinity of T_m. It then decreases again and disappears at lower temperatures. The reason for this latter behavior is obviously due to the rapidly decreasing mobility of the molecules at lower temperatures, so that one would expect the decline to be proportional to the increase of the viscosity. Aside from this, N depends in the most general way upon the probability of the formation of centers within the system. This probability is obviously controlled by the following factors: the number of molecules within the system, the mobility of the molecules within the liquid and the configuration of the crystal lattice characteristic for the particular liquid. Qualitatively speaking, it can be said that the smaller the symmetry of the crystal lattice and the farther the molecular configuration of the lattice is removed from that of close packing, the less is the probability of the formation of a nucleus.[2] Finally, certain other factors have to be considered, such as molecular association at temperatures slightly above the melting point (H_2O) as well as the presence of surfaces within the liquid such as colloids and suspended particles in general.

The second main factor[1] is the linear rate of crystallization V, which characterizes a liquid in a way similar to N and has also a qualitatively similar dependence on the temperature; as shown in Fig. 2b, it rises from zero to $T \leqq T_m$, attains a maximum, remains constant for a certain interval and then declines towards zero. The causes of this behavior are somewhat analogous to, although more complex than, those for N.

The difference between a substance with a high N and a small V and one with a small N for a large V is that under the same cooling conditions a polycrystalline conglomerate would result in the former, and an oligo- or even single-crystalline habitus in the latter case. One can thus predict that liquids with small N and small V should have a tendency to vitrify, provided they are cooled sufficiently *rapidly* to a temperature where N and V are negligible.

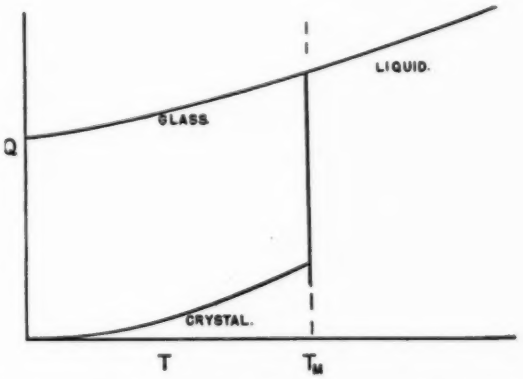

FIG. 1. $Q(T)$—Diagram for the liquid, vitreous and crystalline state of a substance in general. (T_m = temperature of fusion.)

One result of these considerations is that it should be possible to obtain every substance in either a vitreous or a crystalline state, provided that the proper conditions are maintained during the critical interval of temperature where N and V have large values. This postulate, however, has been verified for only a limited number of substances.

[1] G. Tammann, *Kristallisieren u. Schmelzen* (Leipzig, 1903); *Aggregatzustände* (Leipzig, 1923); *Der Glaszustand* (Leipzig, 1932); Zeits. f. anorg. Chemie **222**, 371 (1935); Abh. Ges. Wiss. Göttingen **3**, 92 (1937).

[2] A. Goetz, Zeits. f. Krist. **89A**, 310 (1934); Pap. Disc. Int. Conf. London II, 62 (1934); Phys. Rev. **47**, 257 (1935); A. Goetz and S. Scott Goetz, Naturwiss. **26**, 427 (1938); Proc. Am. Phil. Soc. Sept. (1938).

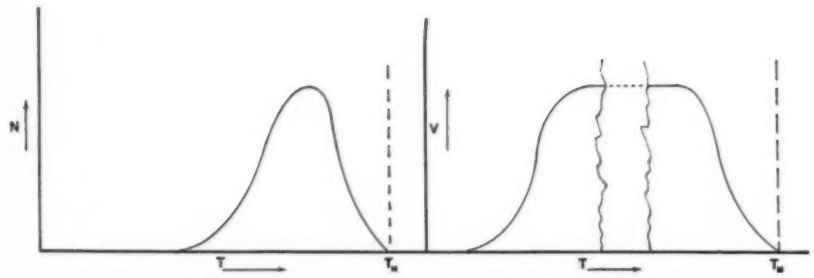

FIG. 2a. $N(T)$—Diagram representing the variation of the formation of crystallization centers with temperature.

FIG. 2b. $V(T)$—Diagram representing the variation of the linear rate of crystallization with temperature. In the omitted temperature interval V remains constant.

b. The rôle of crystallization in the cold death of cells

The irreversible changes which organic matter undergoes when exposed to low temperatures are of so involved a nature that even for the limited field of this paper certain general remarks have to be made.

From the highly diversified literature on the subject of exposing live matter to temperatures below room temperature[3] it is evident that there exists a form of cold death which may be termed *constitutional* (*CD*). It occurs if the organism is kept below its normal temperature longer than its energy supply lasts for counterbalancing the adverse effects of the cold. From this it follows that this *CD* can occur at any subnormal temperature before freezing, but the time factor as well as the type of organism will have a large influence upon the effects observed. The phenomenon of *CD* is outside the scope of this paper.

The other type of destruction of organic matter due to low temperatures is that caused by the crystallization of the cell contents or liquids surrounding the cell, causing either a rupture of the cell membranes or some form of irreversible disorder within the cell so that after thawing, the cell does not resume its activities characteristic for the live state. This phenomenon will henceforth be called *physical* cold death (*PD*). When death occurs below the freezing point this *PD* as the only death cause is apparently restricted to the simplest forms of life, whereas, for higher forms it is often not possible to decide whether *CD* or *PD* caused the destruction. The numerous reports and experiments which claim the occurrence of "supercooling" in live matter fall into this realm. It has been described by several authors[4] that live cells have the tendency to supercool, that is, that the cell content remains liquid although the temperature stays below zero. If the temperature is reversed *before* crystallization starts, the process proves to be reversible, i.e., the cell remains alive. Very early similar phenomena have been found by Bachmetjew[5] on fairly high forms of organic matter, such as larvae of insects, which proved to be able to supercool over fairly large ranges down to $-15°$ where crystallization suddenly started, causing the death of the organism. The well-known freezing curve, Fig. 3, demonstrates that the irreversibility sets in with the beginning of spontaneous crystallization, indicated by the sudden rise of temperature from the minimum temperature to the freezing point, due to the display of the heat of crystallization. As soon as the organism is made to display this heat, death occurs. There seems to be no doubt that this death is *PD*, although it is not easily decided whether the tendencies towards supercooling

[3] J. Bělehrádek, *Temperature and Living Matter* (Berlin, 1935).

[4] A. Åkerman, *Studien über den Kältetod und die Kälteresistenz der Pflanzen* (Lund, 1927): P. Bachmetjew, Zeits. wiss. Zool. **66**, 521 (1899); **67**, 529 (1900): E. Bahrmann, Zeits. f. Biol. **92**, 366 (1932): H. Bartetzko, Jhrb. wiss. Bot. **47**, 57 (1910): A. T. Cameron and T. I. Brownlee, Am. J. Physiol. **7**, 115 (1914): R. Chambers and H. P. Hale, Proc. Roy. Soc. **B110**, 336 (1932): H. W. Fischer, Beitr. z. Biol. d. Pflanz. **10**, 133 (1911): R. Höber, *Physikalische Chemie der Zelle und der Gewebe*, 6. Aufl. (Leipzig, 1926): H. D. Hooker, Proc. Am. Soc. Hort. Sci. 204 (1920): P. Jensen, Zeits. f. allg. Physiol. **14**, 320 (1913): H. H. Knight, Rep. State Ent. Minnesota **19**, 50 (1922): T. Kodis, Ctbl. Physiol. **12**, 593 (1898): T. Moran, Proc. Roy. Soc. **B105**, 177 (1930): T. F. Morrison, J. Gen. Physiol. **7**, 741 (1924): R. Newton, J. Agr. Sci. **14**, 178 (1924); Res. Bull. Univ. of Alberta, Coll. of Agric. **1**, 1 (1923): N. M. Payne, Ecology **7**, 99 (1926); J. Morphol. **43**, 521 (1927): R. Pictet, Rev. Sci. **52** (1893); Arch. Sci. phys. et nat. Per. 3, T. **30**, 293 (1893): L. Pignorini, Annuar. Stat. bacol. Padova **46**, 176 (1931): F. A. Pouchet, J. de l'Anat. **3**, 1 (1866): R. Rein, Zeits. f. Naturwiss. **80**, 1 (1908): W. Robinson, J. Agr. Res. **37**, 749 (1929): J. T. Rosa, Proc. Am. Soc. Hort. Sci. **207** (1921); Missouri Agr. Exp. Sta. Res. Bull. **48** (1921): K. Shibata, Mem. Tohoku Univ. **16**, 91 (1935): R. Tigerstedt, Wint. Hdb. d. vergl. Physiol. III/2, **1** (1910–14): R. Weigmann, Zeits. f. wiss. Zool. **134**, 641 (1929).

[5] P. Bachmetjew, Mem. l'Acad. Imp. Sci. **10**, 63 (1900); *Temperaturverh. bei Insekten* (Leipzig, 1901).

characteristic for live organisms are of a constitutional or a physical nature.

It is, however, definitely proven that there are numerous forms of organisms to which the *CD* does not apply, as shown by the experiments on thoroughly dehydrated protozoan[6] and even metazoan[7] forms which withstood, without particular precautions, temperatures down to the boiling point of He (4.2°K). In these cases the *PD* was avoided by complete dehydration so that no substance for crystallization was present. Experiments of this type are of course restricted to seeds, spores and infusoria, and it is also obvious that neither the time of exposure nor the temperature has any influence.

The question arising from these known phenomena is: is it possible to expose *nondehydrated* organisms to low temperatures without destroying their potential life? It is known for a number of bacteria, moulds and fungi which contain only very small quantities of liquids, that they survive very low temperatures without dehydration, whereas, it is also known that the majority of protozoa and plants cannot be cooled without the destruction of life.

c. Conditions of vitrification

It has been stated above that the *PD* consists in the crystallization of the cell plasma. This leads to the assumption that if conditions under which the organism is cooled can be so arranged that vitrification is more probable than crystallization, the *PD* should be avoided. In contradistinction to crystallization, vitrification would not disturb the molecular arrangement of the cell contents, and also, the more macroscopic effect of crystallization, the lesion of the cell membrane, is impossible.

The greatest handicap in experiments connected with the vitrification of water and diluted aqueous solutions is the unusually high value of N and V (see Ia) which render any attempts at the vitrification of organisms very difficult.

The fundamental conditions to be fulfilled for obtaining the vitreous state are the following ones:

(1). Since for a given value of N the probability for the formation of a nucleus in a given system depends upon the *number of molecules available*, the system should be chosen as *small* as possible, i.e., to contain a minimum of molecules. The minimum size of a system for organic matter is a single cell; among different cells the smallest should have the largest probability of vitrification.

(2). For a given N and a given number of molecules, the probability of the occurrence of a nucleus depends upon the temperature (in the way shown in Fig. 2a) and the time during which the system is at a certain temperature. As N decreases exponentially towards low temperatures, after the maximum, it is very important to *cool* the system *as quickly as possible* over the temperature interval in which N has large values. Below this "critical" temperature interval, the cooling rate is of no importance as far as N is concerned. From this it is obvious that the ultimate temperature to which the system is cooled is irrelevant as long as it lies below the "critical" temperature range.

(3). It has been stated above that N depends upon the complexity of the molecular configuration in the crystal. As it is not possible to change the chemical constitution of the aqueous solution within and around the organism without damage to the latter, the only way consists in increasing the surface exposed to the liquid; this can be accomplished by the addition of complex colloidal matter causing, due to the introduction of surface forces, a decrease of N. Such substances

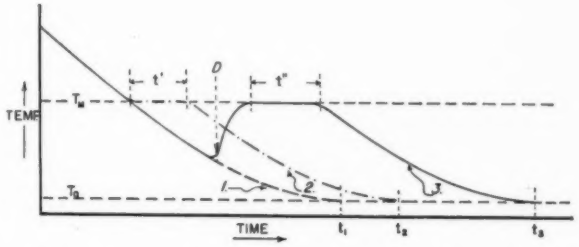

FIG. 3. Temperature-time function for: (1) continuously cooling substance; (2) substance crystallizing at T_m, remaining at T_m for the time t'; (3) substance supercooling down to D. Due to the emission of the heat of crystallization T rises to T_m for the time t''. Type (3) is characteristic for organic substance. Death sets in at D.

[6] P. Becquerel, C.r. Acad. Sci. **181** (1925); **188**, 1308 (1929); **190**, 1134 (1930); **194**, 1378 (1932); **194**, 2158 (1932); **202**, 978 (1936); *Travaux Scientifiques* (Paris, 1932): H. T. Brown and F. Escombe, Proc. Roy. Soc. London **62**, 160 (1898): W. F. Busse, Bot. Gaz. **89**, 169 (1930): P. G. Rahm, Nat. Woch. **19**, 619 (1920).

[7] P. G. Rahm, Versl. Akad. Amsterdam Afd. Natuurk. **30**, 299 (1921); Zeits. f. allg. Physiol. **20**, 1 (1923); Verh. D. Zool. Ges. **106** (1924).

(hydrosoles of organic substances) are gelatine, agars, glues, the addition of which does not affect the organism.

(4). The spontaneous rate of crystallization depends upon almost the same physical factors as N; accordingly, the conditions for vitrification with respect to N hold also for V, with the possible exception of (3) in which latter case the addition of colloidal matter reduces V in certain cases.

It is generally to be assumed that V is a much more critical factor than N for the avoidance of *PD*.* In order to control V, it is necessary to consider the critical temperature interval for V just as accurately as for N. Another point to be considered with respect to V is the *time of exposure* to low temperatures. As V, for thermodynamic reasons, will become zero only at zero temperature, it is to be expected that a gradual, though slow, crystallization out of the statistical arrangement of the glass will go on with time. One should therefore expect that the time of exposure will have an effect upon the probability of the survival of the organism unless the temperature is chosen so low that the value of V is sufficiently small to be negligible for time intervals on a terrestrial scale.

(5). If it is desired to warm the vitrified substance while preserving the capacity for life, condition (2) has to be fulfilled in *warming as well as in cooling* in order to avoid crystallization when the substance passes the critical temperature interval in the direction towards room temperature. If the final temperature be chosen sufficiently low (that of liquid air) the warming process is not as critical as the cooling process in this particular regard, because the critical temperature interval for aqueous solutions ends at approximately $-110°C$[8] so that an interval of 70° is available for the time of transfer from one bath to the other, where the warming rate cannot be forced.

* It can be taken as a generally accepted fact that a perfect crystal is just as well an ideal abstraction as a perfect glass. The x-ray spectroscopic evidence has not yet proved the existence of either of the ideal states. In the case of the vitreous substances, even fused quartz has been proven to contain small realms of crystalline molecular array, the dimensions of which are far below the limit of optical detectability. To speak of the vitreous state of a cell is thus an inaccuracy and means that a cell is "vitrified" if the size of the crystalline realms are smaller than dimensions fatal for the particular cell. This relation may serve to explain that organisms of different types but of approximately the same dimensions and structure cooled under identical conditions do not survive with the same probability. The size of the realms is determined by V, whereas N determines their concentration.

II. Technical Considerations

a. Techniques of vitrification

In the following, a number of different techniques will be briefly described which have been employed by the authors in order to realize experimentally the conditions of vitrification discussed in (Ic).

Condition (1) calls for small systems of molecules, which means either the isolation of the single cell as the minimum size of a system or, where the cells are small enough, the use of small droplets or thin layers (membranes). This has been done in cases where bacteria were used by spraying liquid cultures through nozzles similar to atomizers. This method is applicable only where the organism is small and has sufficient mechanical resistance to stand the shear to which it is subjected when passing the nozzle at the speeds necessary to atomize the more or less viscous liquid.

If the cells are too delicate, it is possible to resort to a technique which produces a thin membrane of the cell-containing culture medium in a large platinum loop. In this case the largest surface possible for a given volume can be created in a relatively simple manner.

Condition (2) requires a high rate of cooling over the critical temperature interval, which is not as easily realized. It is obvious that the culture medium should be brought in contact with the low temperature bath as quickly as possible, and also that this bath should have a temperature as low as conveniently possible, e.g., that of liquid air (90°K). This can be done by shooting the spray under pressure into the cooling bath, or by dropping the membrane with its holder as quickly as possible into it. Experiments prove, however, that all such efforts to overcome V with the cooling rate are rendered futile by the "Leidenfrost phenomenon" which consists of the formation of an insulating gas layer around the warm object, rendering a quick

[8] E. F. Burton and W. F. Oliver, Proc. Roy. Soc. **153A**, 166 (1935).

temperature exchange impossible. It is obvious that this phenomenon will always occur when the *boiling point of the cooling medium lies below room temperature*, i.e., the temperature of the medium at its introduction. As the cooling bath has to have a very low temperature, only very few substances for such cooling purposes are available (as they must also be liquid at low temperature).

Another condition has to be imposed upon this substance which is also imperative—it must be insoluble in water. The only substance which was found to fulfill these conditions is isopentane (C_5H_{12}) with a boiling point at 28°C and a melting point at −159.6°C.[9] * As isopentane has, like most other substances of very low crystallization temperatures, small values for N and V, it can be undercooled to the boiling point of N_2, where it remains a clear liquid of syrupy consistency. Fig. 4 shows the arrangement where a container with isopentane is submerged into a Dewar vessel containing liquid air. The temperature of the pentane is easily measured with a thermocouple or pentane thermometer.

The realization of condition (5) is also easily obtained with the use of volatile hydrocarbons; the substance is transferred as rapidly as possible from the pentane bath into a bath of petrol-ether at room temperature and is moved vigorously in the latter, in order to further a rapid temperature exchange.

Condition (3) may find its fulfillment in a number of ways. The introduction of gelatine has been used fairly early in the work, and observations similar to those of Luyet[10] have been made.

b. The use of yeast (Saccharomyces cerevisiae)

With regard to the previous considerations, it seemed advisable to choose organisms for the low temperature experiments which are easily obtainable in pure culture, and where the individual cells are large enough not to necessitate the use of microscopic objectives of extremely short focal length, causing inaccuracies in the counts. The chief condition for experiments of surveying character seemed to be a sensitivity of the organism to exposure to low temperatures such that a sufficient number of individuals survive under normal (i.e., not too adverse) freezing conditions, and the nonoccurrence of *CD* within the time of the experiment.

The yeast was obtained as commercial bread yeast and suspended in Ringer's solution, where it remains stable for a number of hours. For each set of experiments new yeast was used; this procedure was chosen as it proved to give more uniform results than those obtained with the same yeast taken from liquid nutrient media. A general advantage of the use of such cells consists in the applicability to them of the technique of producing monocellular layers on gelatine films (IIc). This state is very easily checked in the ultra-microscope, where the superposition of two cells can be seen if present.

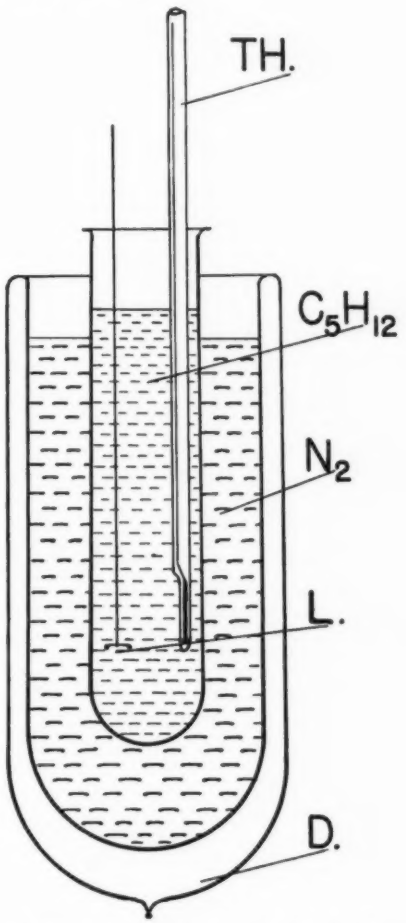

FIG. 4. Scheme of cooling apparatus. *D*, Dewar vessel containing liquid nitrogen (N_2); suspended in it a container with isopentane (C_5H^{12}); Th, pentane thermometer; *L*, submerged platinum loop holding culture membrane.

[9] *International Critical Tables*, Vol. 1, p. 61, III, p. 220.

* The use of isopentane for such experiments is only possible since it does not affect the cells as a solvent nor by any observable chemical reaction.

[10] B. J. Luyet, Biodynamica **29**, 1 (1937); Phys. Rev. **53**, 323 (1938).

FIG. 5. Microphotograph of dead and live cells of Saccharomyces cerevisiae (apl. cond. 1.4, exc. 8 mm; obj. apochr. 40×; magn. 500×; orange +green filter; Agfa Superpan; tungsten arc).

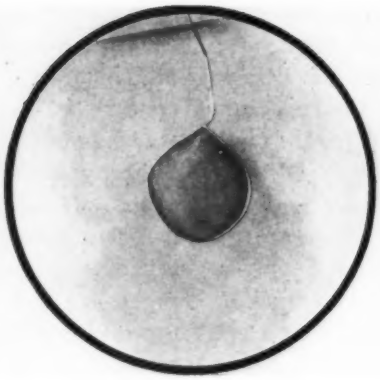

FIG. 6. Microphotograph of culture membrane containing yeast cells, in platinum loop (magn. 2.5×).

FIG. 7. Microphotograph of culture membrane containing yeast cells (magn. 48×).

For counting purposes, however, direct illumination has to be used since the ultra-microscope does not permit visual distinction between stained and unstained yeast cells (cf. below).

c. Determination of the death rate δ

A quantitative experimental study of the *PD* of organic matter requires, besides an adequate experimental technique for the production of the conditions of vitrification, the establishment of a definite criterion of the live or dead state of the cell. The most obvious way is the growth of cultures of cells treated, if the organisms represent bacteria, fungi or protozoa easily cultivated. This technique has been used generally in the work quoted,[6] also in the first experiments of the authors. It is, however, not indicative of the actual death rate because of the purely qualitative indication of the existence of some or even *one* surviving cell.

In fact, if the death rate δ, that is, the ratio, Δ/N, of the number of dead cells, Δ, to the total number of cells present, N, is to be determined quantitatively, a criterion for the dead state of a cell must be developed. Of the several criteria of "death," such as loss of ability to reproduce, etc., the loss of resistance to the penetration of a standard concentration of an aqueous solution of methylene blue was chosen in our experiments.

This method was decided upon after considerable experimentation with various differential staining methods using stains of colloidal nature, such as congo red and trypan blue.*[11,12] It was, however, found that in the case of yeast, the cold death is not indicated to a full extent by a permeability of the cell membranes to colloids, even those of such small particle sizes as trypan blue.

Of course, all molecular stains have a lethal effect if they penetrate into the cell in sufficient concentrations. However, live cells can withstand very considerable concentrations by preventing the stain from passing through the membrane. If the cell is weakened, the stain enters and accumulates inside of the cell, with destructive effects. Experience shows also that the concentration of stain in a dead cell is many-fold higher than the concentration of stain in the surrounding medium, and it can easily be shown that the medium is completely discolored if the cells it contains are killed. This is illustrated in Fig. 5 which is a microphotograph of yeast cells, part of which have been killed by exposure to low temperatures. The dead cells appear black, the live ones white; the background, consisting of the stain-containing medium, is gray.

* It is known that a number of stains of colloidal character do not affect micro-organisms while they are alive, and that the dye can stay in contact with the cells for a considerable length of time if not too concentrated. The use of this fact for a method of differentiation was first made by Seyderhelm and collaborators, (reference 11) who used a mixture of congo red and trypan blue known as "Seyderhelm stain." It was applied first to leucocytes as a differential stain and also to protozoa (reference 12).

[11] R. Seyderhelm and W. Lampe, Dt. Med. Wochenschrift Nr. 32 (1923): R. Seyderhelm, Dt. Med. Wochenschrift Nr. 5 (1925).

[12] K. Pietschmann, Arch. f. Protistenkunde **65**, 3 (1929).

FIG. 8. Microphotograph of unexposed Saccharomyces cerevisiae, used for the determination of δ_0 (apl. cond. 1.4, exc. 7 mm; obj. apochr. 20×; magn. 250×; orange+green filter; Afga Superpan; tungsten arc).

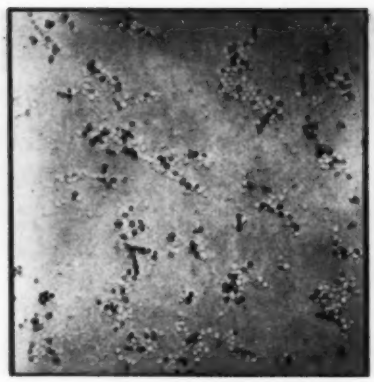

FIG. 10. Microphotograph of Saccharomyces cerevisiae, once exposed to −185°C under conditions partly favoring crystallization (optics same as for Fig. 8).

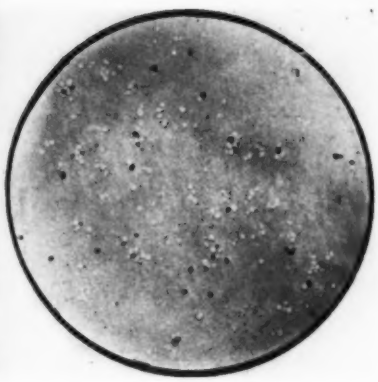

FIG. 9. Microphotograph of Saccharomyces cerevisiae, once exposed to −185°C under vitrifying conditions (optics same as for Fig. 8).

The main consideration, however, in the choice of the death criterion lies in the experimentally proven fact that the *PD* affects the cells in such a way that they become permeable to this particular stain.* The concentration of this stain was chosen in a range where the death rate measured was very little affected by a variation of concentration (1/200).

This technique becomes very simple and seemingly more reliable than any other method if a number of technical precautions are observed. The death rate δ is determined simply by placing a drop of the treated culture containing the dye on a slide under the microscope and taking one or several photographs of it. An enlargement of the photograph is made and the number of stained and unstained cells counted.

Two conditions have to be fulfilled here. It is important to filter the illuminating light in order to produce a maximum contrast between the stained and unstained cells, i.e., the light should contain chiefly the colors complementary to those of the dye used. This condition being very important, it renders it necessary to find, either by trial and error, or by spectroscopic methods, the proper filter combination for each dye. Furthermore, the sensitivity of the photographic emulsion has to be chosen properly. The microphotographs show thus white and black cells which can easily be counted.

Secondly, it is important to choose the magnification and the concentration of the preparation in such a manner that a large number of cells (several hundred to several thousand) are on one photograph, in order to obtain fair statistical percentages. The errors connected with this method are small and can occur only if more than one layer of cells is in the preparation, as, if several cells lie on top of each other, the effect of a dark cell may be created. This can be avoided by applying the following technique: the carefully cleaned slide is slightly heated and then covered with a thin layer of cleared gelatine solution. The slide is then allowed to cool and dry until the gelatine is almost completely hardened. A concentrated drop of the culture containing the stain is then put upon the gelatine coat and distributed over the latter by rubbing under very gentle pressure with a fingertip until all of the gelatine is equally wetted. A wetted coverglass is then slipped over the slide and the surplus liquid soaked up with filter paper. Investigation has shown that δ is not increased by this manipulation. Under low magnification one finds large regions on the preparation consisting of 10^3 to 10^4 individuals in monocellular arrangement. Counts within these realms prove to be very reliable.

Another precaution has to be taken if the organisms are sensitive to blue light or to heat.

* It may be noted that many other molecular stains, such as the saffranines, Bismarck brown, corallines, rose bengal and neutral red penetrate the cell in the case of death by heat but they fail to permeate (or if a penetration takes place it is at the border of visibility) in the case of *PD* if concentrations are used which are small enough not to affect the cells within a short time.

In this case they are destroyed during the time of observation by the illuminating light source. In such cases it is possible to observe a rapid increase of stained cells within a short time during observation of the slide. This renders it necessary to use effective heat filters and also to shorten as much as possible the time of exposure to the light.

d. Experimental procedure

The stable yeast suspension in Ringer's solution was kept always at approximately the same standard population of $2\times10^6/mm^3$, checked with a haemocytometer. From this suspension a very thin membrane was formed in a platinum loop. It proved easy, with sufficient experience, to form the membrane of such thickness that it contained only a single layer of cells.

Figures 6 and 7 are microphotographs of such membranes. The membrane was then plunged into the pentane bath (IIa). The impact upon the surface will not destroy the membrane if the cooling rate is so large that the membrane instantaneously becomes mechanically rigid. For rapid warming, either the upper pentane layer was warmed, or a second tube, filled with a neutral volatile hydrocarbon at room temperature was kept in readiness, and the loop was transferred as rapidly as possible into it.

As the membrane adopts this temperature instantaneously, it was carefully removed after a few seconds and its contents mixed with a standard quantity of stain solution and placed upon a gelatine slide in order to produce a monocellular layer (IIc). The dead cells then appeared dark, as previously described. Figs. 8, 9 and 10 are microphotographs of such preparations.

As experience showed that different samples of commercial yeast contained a different percentage of dead cells (δ_0), this quantity was determined each time immediately before the beginning of the experiment with the same staining and counting methods. Fig. 8 is a microphotograph of a typical unexposed sample.

III. Experimental Results

a. Death rate under conditions especially favorable to crystallization

The yeast was suspended in Ringer's solution in concentrations of approximately 10^9 cells per cm^3 and cooled to the temperature of liquid air at comparatively low cooling rates. The preparation was left at this temperature for a few minutes and then warmed to room temperature. The death rates thus obtained varied considerably for different experiments, as the method used did not permit of the exact reproduction of the cooling rates. The average values obtained are given in Table I.

Table I.

Approx. cooling rate (deg. sec.$^{-1}$)	20	6	3	1
Approx. death rate (δ)	0.29	0.49	0.70	0.75

Table II. ($v\sim10^3$ *to* 10^4 *deg. sec.*$^{-1}$)

t	N	D	δ	δ'
0	639	7	$0.011=\delta_0$	
Circ. 2′	2232	194	0.087	0.078
Circ. 2′	1071	141	0.131	0.120
Total	3303		Average	0.099

Table III. ($v\sim10^3$ *to* 10^4 *deg. sec.*$^{-1}$)

C_g	t	N	D	δ	δ'
0	0	822	57	$0.069=\delta_0$	—
1/2500	2′	501	74	0.147	0.078
1/250	2′	447	67	0.149	0.080
1/50	2′	390	50	0.128	0.059

There are indications that with further decrease of the cooling rate a death rate of 100 percent ($\delta=1$) can be reached.

b. Death rate under conditions especially favorable to vitrification

The next step consisted in reversing the physical conditions of cooling by applying the principles set forth in Chap. IIc.

The quantitative results presented in Table II. are obtained with the loop-method (Chap. IIb) for T_0 between -150°C and -185°C on yeast suspensions identical in nature, age etc., with the suspensions used previously.

As the submersion was done by hand the rate of cooling ($v=dT/dt$) is not expected to be the same in different experiments, for large values of v are required in view of the magnitude of V for

TABLE IV.

t	lgt	N	D	δ	
0		1312	16	$0.012=\delta_0$	
5′	0.70	1309	405	0.309	0.318
5′	0.70	1017	334	0.328	
17′	1.23	1252	391	0.312	0.324
17′	1.23	1191	402	0.337	
60′	1.78	2145	655	0.305	
120′	2.08	1489	431	0.289	
210′	2.32	1216	348	0.285	
1080′	3.03	858	291	0.339	
6000′	3.78	1976	641	0.324	
Total		12453	Average	0.312	

aqueous solutions. In the subsequent tables the following symbols are used:

t = Time of exposure;
N = Total number of cells present in the photograph;
D = Number of stained cells;
$\delta = D/N$ = Apparent death rate;
δ_0 = Death rate already existing in the preparation before exposure to low temperature;
$\delta' = \delta - \delta_0$ = Actual death rate by exposure;
v = Rate of cooling.

Figures 8 and 9 represent microphotographs of preparations before and after exposure under these conditions.

In accordance with condition (3) (Chap. Ic) the effect of colloidal admixtures upon δ was tested, with the results given in Table III (C_g gelatine concentration).

Although the material so far collected is not sufficient in volume for a final quantitative statement it is evident that:

(1). Exposure to low temperatures under vitrifying conditions *increases the percentage of surviving cells from 25 to 90 percent.*

(2). Addition of gelatine decreases δ still further.*

This appears to prove the previous postulate that *PD and crystallization of the cell are defined functions of each other, and that by suppressing the crystallization the death rate can be controlled.*

* The results in Table II are unfavorable to δ because of the high value of δ_0 which indicates a low vitality of the particular preparation used.

The definite proof depends upon a quantitative determination of $\delta = f(v)_{T_0}$ for which the primitive methods employed so far are insufficient. Results with improved apparatus will be published soon.

c. Death rate under conditions favoring the coexistence of the vitreous and the crystalline state

In order to determine the influence of the temperature, duration of exposure etc., the cooling conditions for the following experiments were chosen so that δ ranged reproducibly between 0.25 and 0.50 in order to dispense with the necessity of counting very large numbers of cells for obtaining sufficient accuracy.

1. Death rate as function of duration of exposure to low temperatures ($\delta = f(t)_T$).—The procedure of cooling chosen to meet the above condition for the study of the variation of δ with t, was as follows:

A given quantity (5 cc) of a standard suspension of yeast in Ringer's solution was put into a test tube and submerged in liquid air, in order that a relatively slow cooling rate might obtain. A number of tubes were prepared in this manner and exposed for different lengths of time to −185°C, the shortest time being 5 minutes (the minimum time for the complete cooling and thawing process) the longest 6000 minutes. Precautions were taken that the warming speed be the same for all samples. The slides were then prepared according to the above method and the results, condensed in Table IV, were obtained.

In Fig. 11 the results are plotted *vs.* the

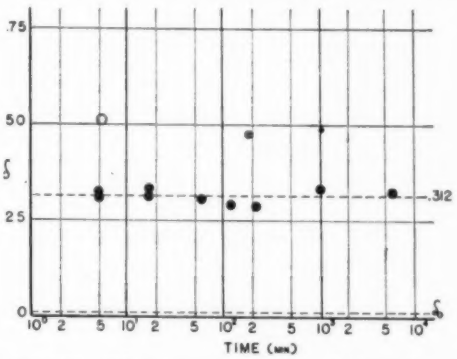

FIG. 11. $\delta(t)$—Diagram representing the invariance of the death rate with time of exposure, the latter being represented on a logarithmic scale. δ = death rate for the unexposed suspension; ● for fresh suspension at −185°C; • old suspension at −185°C, ○ for fresh suspension exposed to 50°C, ⊕ old suspension at −252°C.

logarithm of the time of exposure, where the diameters of the circles (•) represent the estimated accuracy of the counts.

The results obtained show a good consistency of the values and indicate that, in agreement with postulate of condition (4) in Ic, *the duration of exposure does not affect* δ, even if T is varied by a factor >1000, *if the temperature is far below the critical temperature interval.*

The reaction of an older yeast suspension (48*h*) to $-185°C$ under the same conditions shows a higher δ (.48), indicated in Fig. 11 as ..

2. Death rate as function of temperature ($\delta=f(T)_t$).—In order to test the conclusion made previously that below the "critical" temperature range the temperature should not have any influence upon the death rate, a preparation identical with those described in (IIIc, 1) was exposed to the boiling temperature of hydrogen ($-252°C$). The experiment was performed as follows: 1 cc of the suspension was sealed in a glass tube and submerged first in liquid air for the purpose of precooling. It was then transferred quickly into a container of liquid hydrogen and left there for approximately four hours. It was then transferred again into a liquid air bath, where it remained 24 hours. Then it was warmed to room temperature at the normal rate, after which δ was measured in the usual manner.

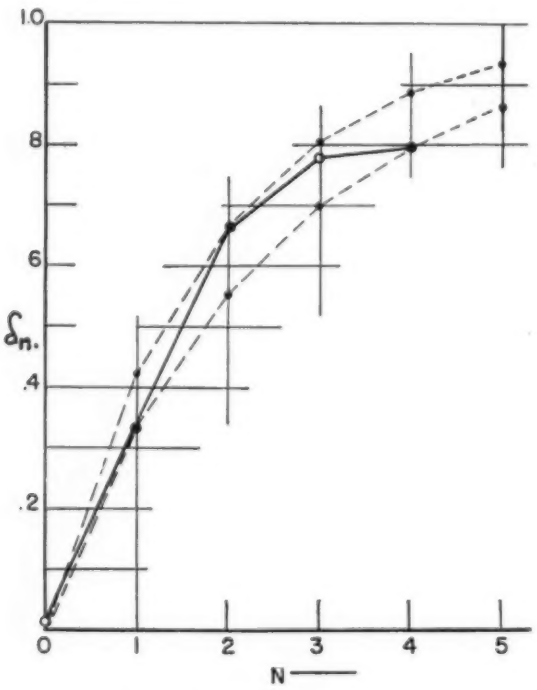

FIG. 12. $\delta_n(n)$—Diagram representing the integral death rate after repeated exposure to $-185°C$ under normal cooling conditions. The full drawn lines represent the observations, the dashed lines the prediction for $\delta=$const., the lower for $\delta=\delta_1$, the upper for $\delta=1-(1-\delta)^{\frac{1}{2}}$.

The suspension was of 48-hour age, characterized at liquid air temperature by $\delta=0.48$ (see IIIc, 1). The value obtained in the liquid air—hydrogen exposure (⊕) proved to be $\delta=0.46$, which is, within the experimental error, identical with the liquid air value. This indicates *the invariance of* δ *with* T *below the critical temperature range.*

Although sufficient data are not yet available for a reliable indication, it may be mentioned that similar experiments have been performed at $-50°C$, that is, within the critical temperature range (marked by ○ in Fig. 11) by means of pentane cooled in a solution of CO_2 in acetone. The value of δ, under otherwise similar conditions, proves to be about 0.5 for an exposure of several minutes for a freshly made suspension, i.e., 18 percent higher than the average $\delta=0.31$ for a fresh suspension at $-185°C$.

3. Death rate as function of the number of repeated exposures to low temperature ($\delta_n=f(n)_{t,\,T_0}$. —A different type of experiment can be devised in order to gain insight regarding the nature of *PD* in organic matter from another angle.

If the same sample is *repeatedly exposed* to low temperatures under identical cooling and warming conditions (v, T_0), the following simple mathematical consideration should be applicable. If N is the total number of cells, D_n the number stained (dead), L_n the number unstained (alive), both after the nth exposure, then: $\delta=D_1/N$; $\lambda=L_1/N$; $\delta=(1-\lambda)$ after the first exposure. The total death rate (determined by count) after the nth exposure is therefore:

$$\delta_n=f(n)_{v,\,T_0}=\sum_1^n \delta\cdot\lambda^{n-1}=\frac{\delta(\lambda^n-1)}{\lambda-1}=1-\lambda^n.$$

The experiments were conducted under similar conditions to those described in IIIc, 1, i.e., for medium values of $\delta(=\delta_1)$. Table V represents the results together with calculated values of δ_n for comparison.

Figure 12 illustrates the difference between the experimental and the theoretical function, which

latter has been calculated up to $n=5$ for $\delta=\delta_{1\,exp}$ and for $\delta=1-(1-\delta_{2\,exp})^{\frac{1}{2}}$.

The observations show a systematic deviation from the theoretical functions beyond the experimental error, as $\delta_{n\,exp}(n)$ increases faster for $n=2, 3$ and again reaches numerical equality for $n=4$ with the expectation of decreasing below the theoretical values for $n=5$. In other words, the behavior of the function indicates that *δ does not stay constant with repeated exposures*, for δ_2 and δ_3 are larger than δ_1 and δ_4. Although the number of counts and experiments are, up to now, not sufficient for a definite statement, the possible causes for this type of deviation will be briefly discussed.

(1). The first exposure weakens a certain fraction of the cells against *PD* but they are not destroyed. These cells cannot resist a second or third exposure and thus contribute largely to δ_2 and δ_3. After all such cells have been destroyed, δ_4 is again normal (the close numerical coincidence for δ_4 in Table V, is of course to be considered accidental). It is also to be expected that for δ_5 the values would be even smaller than predicted because the remaining cells represent a selection of those with the most resistant qualities.

With this assumption it appears nevertheless surprising that the first exposure does not show the largest death rate.

(2). A large fraction of cells killed in previous freezings is physically annihilated by crystallization (bursting the cell membrane) during later exposures to alternatingly low and high temperatures. Thus with each new freezing the number of cells killed during previous exposures is gradually decreased, as these bursted cells become invisible and drop out of the count.

TABLE V.

n	N	D_n	δ_n	$\delta_n=(1-\lambda^n)\delta_1$	$\delta_n=(1-\lambda^n)\delta_2$
0	1312	16	0.012	—	—
1	1200	401	.333	0.333	0.423
2	1359	902	.667	.552	.667
3	1370	1070	.781	.700	.808
4	840	669	.796	.799	.889
5	—	—	—	.865	.936
Total	6081				

In order to check this possibility, the total population for each n was checked with the haemocytometer. Although the accuracy of this method is not sufficiently large, it does not seem probable that the total population decreases considerably with increase of n up to $n=10$. In any case, the existence of such an effect cannot explain the increase of $\delta_{2,3}$ over δ_1, for which only the physiological cause previously discussed appears to account.

The possibility of "weakening" cells by exposure gains probability in view of the fact that in these last experiments small cooling velocities were used, possibly allowing time for destruction by *CD*. It is to be expected that the $\delta_n(n)$ function will change considerably for forced cooling conditions. Work in this direction is continued.

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The Role of Solid Friction in Synthetic Dielectrics

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New synthetic dielectric materials, both of the ceramic and resinous type, exhibit, among other features, a high grade of homogeneity. This will not only affect the mechanical properties, the electrical breakdown strength and the dielectric losses due to layer mechanism favorably, but will reduce also losses due to dipole rotation. In case, namely, dipolar constituents rotate at all in the solid state, dissipation of energy will be caused by the solid friction, which has to be overcome. This latter, on the other hand, can be shown to be related directly to the imperfections of the material, thus indicating the beneficial effect on the dielectric loss angle of a homogeneous structure.

1. INTRODUCTION

IN recent years considerable progress has been achieved in the field of new, synthetic materials, both of the inorganic and organic type.[1] It has become evident that only by means of synthetic products is it possible to surpass a certain limit of quality which cannot be transcended even by highly purified natural materials.

These new products, although far from being satisfactory in every respect, show a great improvement as compared with the previously known ones, especially with regard to their low dielectric loss factor. Apart from this, they possess a low direct-current conductivity, a high breakdown strength, and also their mechanical properties are up to requirements. The least satisfactory is perhaps the heat resistance of some of the organic materials in that they possess a comparatively low yield point.

There are certainly several reasons for the high quality of these materials. One, namely the homogeneity of their structure, seems fairly important, and the following paper will be concerned with an explanation on this basis of their low dielectric loss factor.

Apart from this consideration there is, of course, little doubt that the absence in the synthetic products of all kinds of electrolytic admixtures, such as are frequently present in Bakelite or rubber products, for instance, accounts for their low direct-current conductivity, also at more elevated temperatures; this is, however, not the only point. The low level of dielectric losses needs another explanation on different grounds.

2. REQUIREMENTS FOR ELIMINATING DIPOLE CONSTITUENTS

It is well known[2] that dielectric losses very frequently occur through rotation of dipole molecules in an alternating electric field. Independently of the special theory, dealing with this phenomenon, the mathematical expression for the loss angle contains the total concentration of dipolar constituents as a linear factor. This is the case, indeed, for the original expression derived by P. Debye, and also for others, as long as the concentration of dipoles does not reach a certain limit, at which mutual influence of neighboring dipoles takes place, thus necessitating the addition of terms of higher than first power with regard to the dipole concentration.

It seems, therefore, reasonable to assume that one of the chief aims in producing synthetic dielectrics is to eliminate all dipolar constituents as far as feasible, unless a special product of high dielectric constant is required. Paraffin among the natural products, for instance, is known to be a material with a very low loss factor for this reason. Owing to its low melting point it can only be used as an impregnating material, and attempts have been made to produce dielectrics of higher melting point but similarly low dipole content. The result of these attempts is among others the material known as

[1] A. R. Dunton, Electrician **118**, 129 (1937).

[2] W. Jackson, J. Inst. Elec. Eng. **79**, 565 (1936).

polystyrene, the structure of which has been elucidated by Staudinger[3] and others. Its Martens softening point is 80°C, its loss angle at 600 kc being 2×10^{-4}, and its electric strength at 20°C and $\frac{1}{8}$ in. thickness: 240 kv/cm.[4]

However, the range of synthetic materials would be very limited, if it were restricted to pure hydrocarbon polymerides which are the main representatives of compounds possessing negligible dipole moments. As soon as sulphur, for instance, is introduced, as in the thiokol resins, being condensation products between organic dihalides and metallic polysulphides, the molecule will contain groups with finite dipole moments.

3. Question of Homogeneity

Further in the realm of inorganic materials the requirement of a low dipole content is even more difficult to be fulfilled. Let us consider the new ceramic materials in this connection having steatite, that is magnesium silicate basis. The chief question arises, how these materials, though of dipolar nature, still possess a low loss angle up to radiofrequencies. Comparing these new materials with porcelain, the classical representative of ceramics, the higher alkali content of porcelain has to be considered first, causing part of its high conductivity and loss factor. Another most striking difference, however, is found in their internal structure, as revealed by microscopic investigations.[5] Whereas the microscopic picture of porcelain reveals a glassy medium in which small crystals of mullite and quartz are interspersed, that of the new ceramic materials is mainly constituted by a very dense structure of more or less uniform crystals of Klinoenstatite with only a small percentage of a glassy phase. The whole structure is more regular, homogeneous, and it seems likely that the superiority of magnesium silicate as basis, as compared with aluminum silicate can be accounted for by its suitability to yield more homogeneous structures.

This statement, however, might seem somewhat surprising with regard to our previous one, namely that the losses are due to dipolar molecules, since, according to the generally adopted view, such a loss mechanism has very little to do with a heterogeneous structure. This latter is known to have an influence only upon losses due to a Maxwell-Wagner mechanism. Although it is certain that this latter plays an important part in low frequency processes for a number of insulating materials, it seems that the role of dipoles is just as important and of the same order of magnitude, even for a number of crystalline materials. The free rotation of single groups is not generally hindered, though the molecules are arranged in a regular lattice. This has been shown among others by W. Jackson[6] by means of measurements on paraffin wax containing cetyl palmitate, further by White and Morgan by measurements[7] of the dielectric constant of certain organic compounds, e.g. ethylene cyanide, at temperatures below their freezing point, the gradual decrease with further decreasing temperature of the dielectric constant in the solid state being an indication of a free rotation of certain radicals in the molecule.[8]

It is, therefore, not sufficient to point out that the homogeneity of the new materials prevents a Maxwell-Wagner mechanism to be developed to a considerable degree, because a finite fraction of the total loss is generally due to dipoles, and the explanation is not complete, unless it can be shown that also the losses due to dipoles will be favorably influenced by the absence of inhomogeneities in the material.

This question, being of primary importance, not only in its physical aspects, but also from the standpoint of the manufacturing of electrical insulating materials, should be explained in the following more in detail.

According to the original theory of Debye, valid for gases and dilute solutions, the loss factor first increases with increasing frequency, but later on decreases, after having passed a fairly sharp maximum. The position in the frequency range of this maximum depends upon the viscosity of the medium, shifting towards higher frequencies with decreasing viscosity.

[3] E. H. Farmer, Ann. Rep. Chem. Soc. **32**, 250 (1936).
[4] A. R. Dunton and A. Caress, J. Inst. Elec. Eng. **79**, 463 (1936).
[5] W. Eitel in Vieweg: *Elektrotechn. Isolierstoffe* (Berlin, 1937), p. 48.
[6] W. Jackson, Proc. Roy. Soc. **150**, 197 (1935).
[7] A. H. White and S. O. Morgan, J. Chem. Phys. **5**, 655 (1937).
[8] J. B. Whitehead, Elec. Eng. **55**, 1180 (1936).

4. Dipole Rotation in Solids

The original theory, however, had to be modified even for liquids, in taking into account the effect upon the dipoles of the electric field of neighboring molecules,[9] the more an alteration with regard to solids is, therefore, necessary. There are a number of different approaches to discuss the behavior of dipoles in solids, some of them being based upon the several, distinct, quantum-mechanically stable positions of the dipole groups. Only one of these different aspects should be dealt with here, since it bears a direct relation to the problem pointed out above, concerning inhomogeneities.

Not looking deeper into the molecular processes, as, of course, a rigorous physical theory ought to, it is possible to state generally that one cannot, with regard to a solid, talk simply of viscosity, as in the case of a liquid, for the reason that the conception of a viscosity, as defined for liquids, necessarily breaks down, if applied to the experimental facts observed on solids. The only case, in which such an application, although with considerable alterations, was feasible, is the plastic flow of solids. It becomes, however, quite impossible for faster processes (vibrations of solids, for instance), even for frequencies as low as about 1 cycle per sec.

As a consequence of this state of matters the author has introduced[10] into the theory the conception of a more general resistance which had to be used instead of the viscosity, when dealing with solids. He called it complex viscosity for the reason that it necessarily implies the existence of a component which is of the nature of a resilience, and is, in the terminology of alternating currents in phase quadrature with the pure viscosity component, the latter being used in a sense as for liquids.

The author has developed formulae for this general viscosity concept, which, however, were not thought to represent a *physical* interpretation, only a mathematical framework, to be substituted later by other expressions, derived either by experiment, or by some special physical considerations. As it happened, it was soon possible to perform such a substitution, by making use of some experimental investigations on the subject of internal friction in solids.

5. Solid Friction and Dielectric Loss

Such work has been carried out among others by A. C. Kimball,[11] who measured the logarithmic decrement of free vibrations in different materials, such as metals, rubber, celluloid, wood, and glass, by submitting an overhanging rod to rotation. Such rods exhibit lateral deviations which prove to be in definite connection with the logarithmic decrement. In assuming (which, as we know, is wrong) the liquid viscosity conception to be valid for solids, it would follow that the logarithmic decrement ought to increase linearly with the frequency. Kimball's measurements have shown, however, that the decrement is independent of the frequency up to a few thousand c.p.s. The conception of viscosity has, therefore, to be replaced by the rule of the constancy of the logarithmic decrement, although one has to bear in mind the merely empirical and possibly approximate nature of this rule. Wegel and Walther[12] have shown by a different method this rule to hold fairly well for glass in the frequency range between 10^3 and 10^5.

The author, in collaboration with W. Jackson[13] carried out an investigation verifying the results of Kimball, and extending them to several dielectric materials, such as ebonite, polystyrene, quartz, glass, and wood, lower frequencies, and higher temperatures.

It is now assumed that the dissipative force the dipoles have to overcome is not of the nature of a viscosity but of the above type of solid friction. In substituting, therefore, the above-mentioned rule into the complex viscosity-frame, an approximate expression for the dielectric loss factor can be deduced, valid, of course, only for the frequency range in which the logarithmic decrement is independent of the frequency. This expression shows that the loss angle itself becomes independent of frequency, at least in first approximation. This conclusion is in good agreement with experimental results generally

[9] P. Debye and W. Ramm, Ann. d. Physik **28**, 28 (1937).
[10] A. Gemant, Trans. Faraday Soc. **31**, 1582 (1935).
[11] A. C. Kimball, *Vibration Prevention in Engineering* (New York, 1932), p. 133.
[12] R. L. Wegel and H. Walther, Physics **6**, 141 (1935).
[13] A. Gemant and W. Jackson, Phil. Mag. **23**, 960 (1937).

obtained from technical insulating materials,[14] showing only a slight variation with frequency of the loss factor, in any case at lower, but sometimes up to radiofrequencies, occasionally with flat maxima and minima, but only seldom with a pronounced sharp maximum, as would follow from the original theory.

The conception of viscosity as well as a pronounced characteristic frequency, corresponding to a power factor maximum, had to be abandoned in this modification of the theory. Instead, the new expression for the loss angle depends not only, as usual, on the concentration of dipole moments in the volume unit, but also contains as factor the value of the logarithmic decrement, as computed from measurements on mechanical vibrations of the material, and assumed to hold also for rotation of dipoles within the same material. The dielectric loss angle is now expressed in terms of the logarithmic decrement of mechanical vibrations.

If, therefore, there is a likelihood of an existing relationship between inhomogeneities in the material and the above logarithmic decrement, then it is proved at the same time that the more homogeneous a material, the lower its dielectric losses.

There does not exist a generally accepted physical theory of solid friction up to the present, but a few attempts have already been made. It seems as if several mechanisms were operative, but it is not yet evident which is the dominating one. Recently, for instance, a theory has been brought forward by C. Zener,[15] explaining the solid friction thermodynamically by local heating and cooling effects due to local compressions and extensions as a consequence of vibrations.

Although such mechanisms certainly play a role in materials possessing an ideally homogeneous structure, yet it seems that in technical materials friction is primarily controlled by unavoidable imperfections of the structure. The same holds, at least in many cases, for the tensile strength, which is determined by the properties of the crystal lattice only in case the specimen does not contain microscopic crevices. Their presence diminishes the tensile strength by two orders of magnitude, so that the ideal strength has but little significance.

6. Internal Slips and Solid Friction

Probably the same position holds for solid friction, losses due to imperfections playing the primary role. How this happens is not yet elucidated in every detail, but it may be pictured roughly in the following way.

The elastic deformation, whether elongation, compression or shear, sets up forces in the material which counteract the external forces. This reaction is operative only up to a certain limit, the mechanical breakdown strength, when rupture takes place, with the consequence that the elastic energy stored in the specimen suddenly disappears and is transformed to a small extent into the surface energy of the rupture area, and, as to its major part, into heat, due to the molecular vibrations set up by the sudden separation.

Considering the so-called weak spots in the material, the existence and significance of which have been proved by several authors, in the first place by A. Smekal,[16] one has to picture them as imperfect structures of microscopic size, interspersed irregularly in the whole volume, and possessing a much lower strength than the bulk of the material. When, therefore, the latter is strained to a point far below its breakdown value, the existing stress will be sufficient to overcome the strength of some of the weak spots, which will give way, in performing a slipping process confined to a microscopic area, and transform the elastic energy stored in that minute volume into heat. As the strain increases, whether in a static process, or a vibrational one, each differential increase of the strain will be accompanied by the slip of a certain amount of internal surfaces, thus by the dissipation of a certain fraction of the total elastic energy into heat.

One of the most important consequences of this explanation[17] is that the total relative loss of energy during one complete cycle of strain-stress variation becomes independent of the frequency, and is the same even for the frequency zero, that is the static process, usually

[14] H. M. Fletcher, Phil. Mag. **24**, 319 (1937).
[15] C. Zener, Phys. Rev. **52**, 230 (1937).
[16] A. Smekal, Die Physik **4**, 17 (1936).
[17] A. Gemant, Trans. Faraday Soc. **34**, 269 (1938).

known by the name of hysteresis loss. This independence of the relative loss is, however, one of the main results of Kimball, Gemant and Jackson, since the logarithmic decrement is exactly half of the relative energy loss per cycle. The theory also accounts for the different types of relation between relative loss and amplitude of vibration, as observed by experiment. By developing the theory quantitatively, the logarithmic decrement turns out to be a simple linear function of the total volume of imperfect spots in the volume unit.

It should be added that the constancy of the logarithmic decrement with frequency can only be valid as long as the time constant of the considered slipping process is smaller than the period of vibration. Above a certain characteristic frequency the specific loss must necessarily decrease. A corresponding change of the dielectric loss angle has then to be expected.

In a recent paper C. Zener[18] shows that imperfections in a material will increase the solid friction on the basis of his thermodynamical theory. His and the author's explanation lead, therefore, to the same conclusion with regard to this important point.

Thus, it is possible to show that a definite relation exists between inhomogeneities of the material on the one hand, the logarithmic decrement of vibrations on the other. We now recall the result of the previous section, namely, the proportionality between the dielectric loss angle due to dipoles and the mechanical logarithmic decrement. Combined with the result just obtained it can be seen that the more homogeneous the material, the lower will be the dielectric loss factor due to dipolar rotation.

The very favorable electric behavior of the new synthetic insulating materials becomes now understandable. Dielectric losses, since this aspect of the question is rather of recent date, has been discussed more in detail. It will be sufficient to add that also the satisfactory mechanical properties and the high breakdown strength of the materials can be accounted for in a straightforward way by their high grade of homogeneity; these latter relations do not, however, require any further detailed explanation.

[18] C. Zener, Phys. Rev. **53**, 90 (1938).

Special Solutions for the Motion of the Powder Gas

An Apology to Mr. Pidduck

IN an article in *Physics*,[1] I stated that Pidduck,[2] in his special solution for the motion of powder gas, had unconsciously made an error in that he assumed that the initial pressure and density were uniform. In the *Journal of Applied Physics*,[3] Pidduck stated that he was perfectly aware of having made the assumption of uniform pressure and that it was a harmless one. He also stated that his results were consistent with mine. In reply to these statements I admitted[4] that his solution for the imperfect gas was equivalent to my solution for the perfect gas but expressed doubts that my solution for an imperfect gas was equivalent to his solution.

I now see, what I should have seen before, that Pidduck based his coordinate system on the *undisturbed* state of the gas rather than on the initial state pertaining to his solution. Such a procedure is not only harmless but perfectly sound. In fact, it leads to a much simpler solution for the imperfect gas than the procedure which I adopted. However, as Pidduck graciously points out, in consequence of this misunderstanding, I obtained a special solution for a perfect gas and also checked the somewhat complicated expression which Pidduck derived for the ratio of the pressure on the breech to that on the projectile.

I apologize for having stated that Pidduck made an error in his solution.

R. H. KENT

[1] Physics **7**, 319 (1936).
[2] Phil. Trans. Roy. Soc. London **A222**, 222 (1921).
[3] J. App. Phys. **8**, 144 (1937).
[4] J. App. Phys. **8**, 144 (1937).